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TECHNOLOGY REVIEW

MAY 2001

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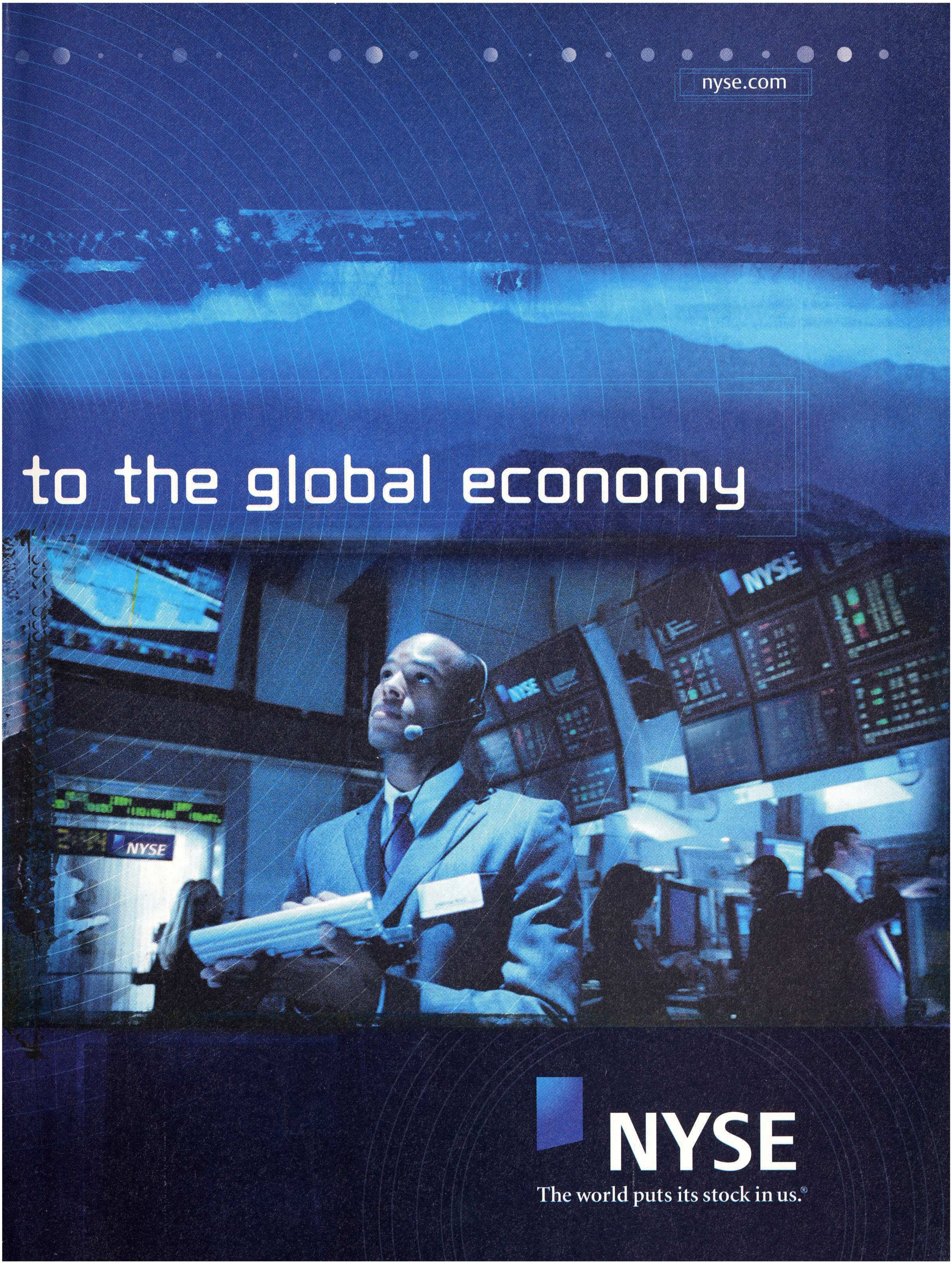
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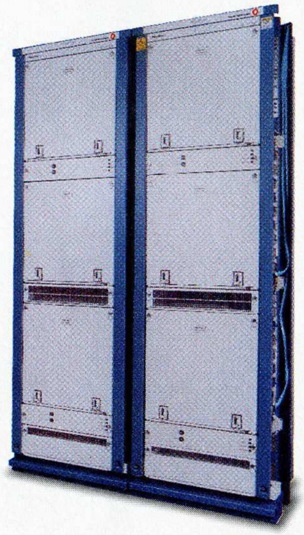

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CONTENTS

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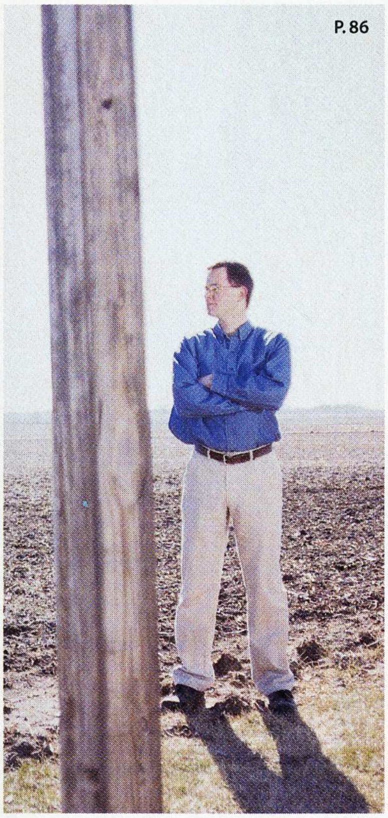
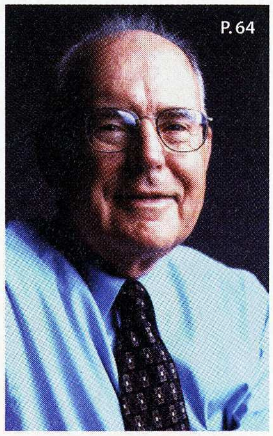
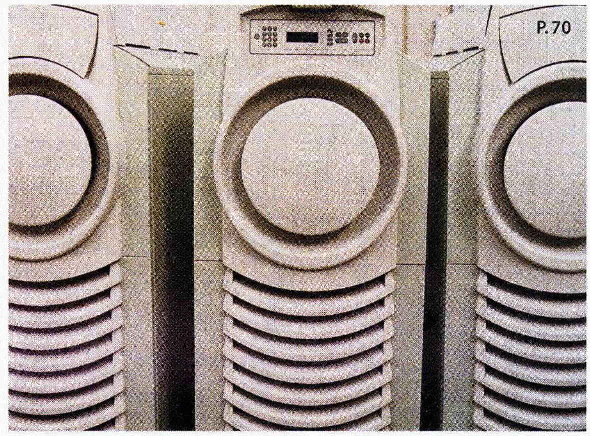
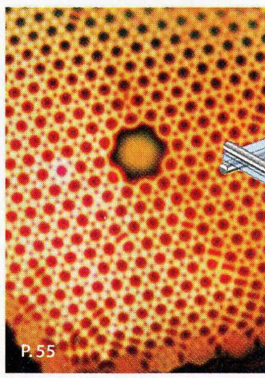
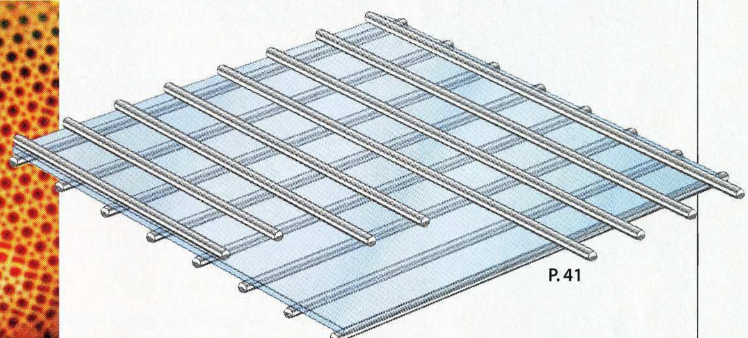




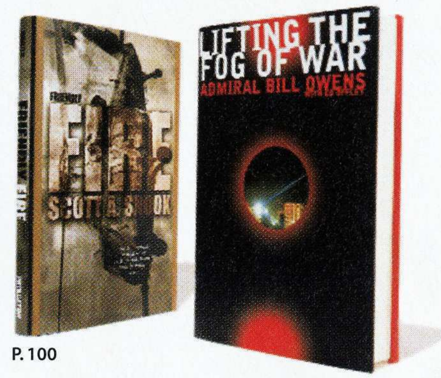






FEATURES

CONTENTS



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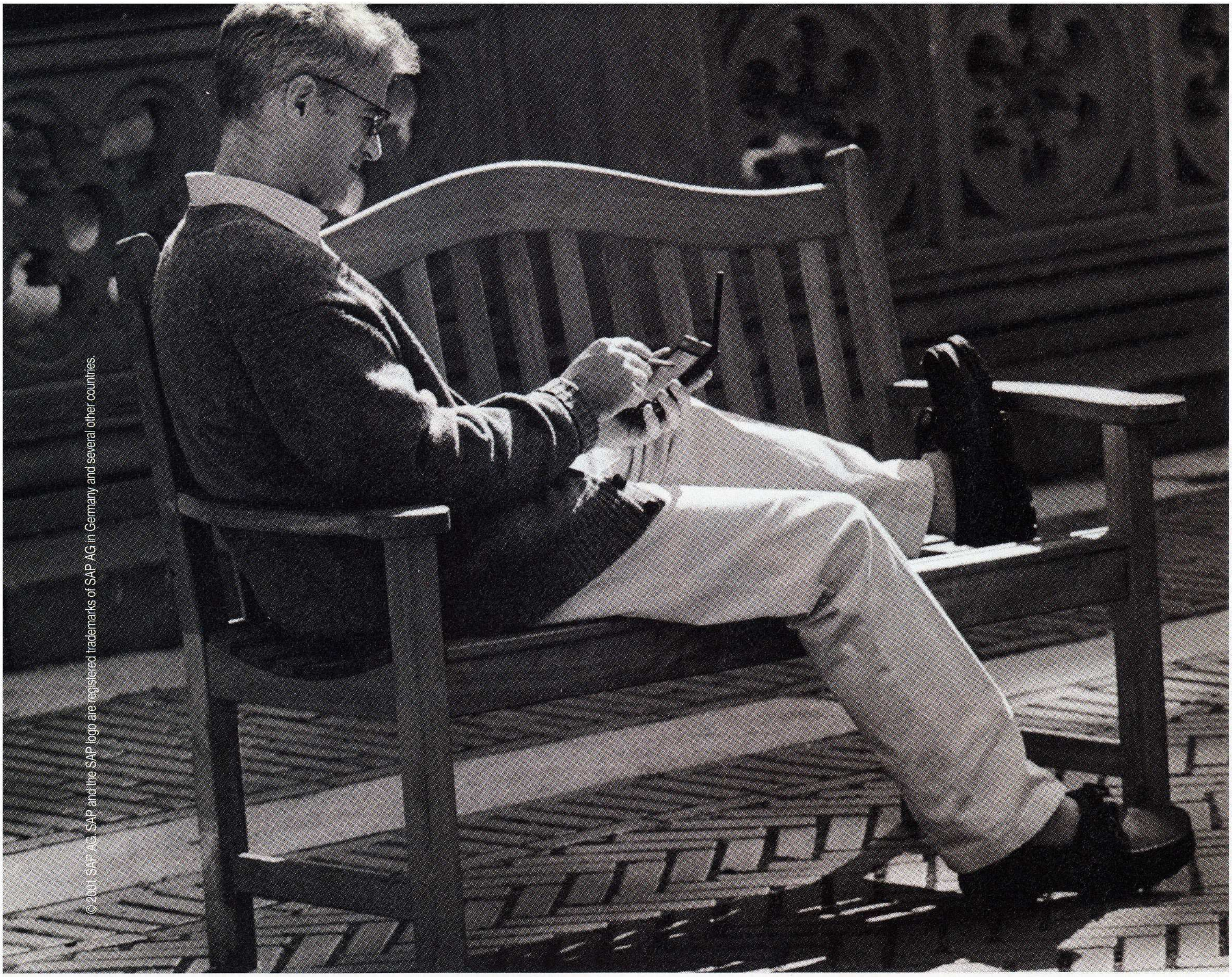
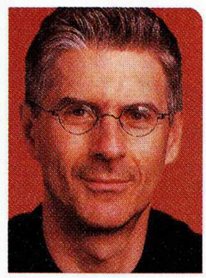


Return to the Future

IN OUR NOVEMBER/DECEMBER 1999 ISSUE, *TECHNOLOGY REVIEW* profiled 100 young innovators who we said were going to create the future. Now we're going to do it again.

The first "TR100" were a remarkable bunch, technologists and entrepreneurs whose accomplishments belied their youth (all were under 35 when chosen). We focused on youth as a way of helping our readers understand the future, which is, after all, our mission. We decided that it's way too hard to actually predict the future. (Even very smart people belly-flop when they try it.) But it is possible to identify some of those who will make large contributions to the not-too-distant future of technology, say the next decade or two.

How do we do that? Well, we spread our net as wide as possible. First of all we're asking all of you, our readers, to nominate young innovators whose work you think will have broad impact. You can find a nomination form in this issue on page 36, or its online equivalent at www.technologyreview.com/magazine/tr100/nominate.asp.



After tapping your collective knowledge, we're going to turn to several other critical networks. First is a distinguished Panel of Judges, including some of the world's most accomplished scientists, technologists and business people. Second is the previous TR100 themselves, the group that is in some ways best placed to identify its peers. Last, but certainly not least, here in our offices in Cambridge, our editors and writers will be using their accumulated editorial experience to find likely prospects.

When we've collected enough names (the first time around we had close to 1,000), we'll begin the process of sorting, screening and judging them to yield a final winnowing of 100. We'll be looking in five critical technology areas, which are, not coincidentally, the areas this magazine covers regularly: hardware, software, telecommunications and the Web, biotechnology, and materials science (including nanotechnology). Of course, there will be a few creative oddballs whose work doesn't fit neatly into any of those big five categories; we'll throw them in too, in the spirit of innovation and subversion.

But that's just the beginning. After we've picked the 100 (and decided on one from their ranks to designate as our "Innovator of the Year" at a gala event here at MIT in mid-2002), we'll use their collective brainpower to try and beat the odds and predict the future. We'll ask each and every one of them to name the key developments in their own fields and talk to us about how those trends will unfold over the next couple of decades. They will know the answers better than anyone else, since they are betting their budding and miraculous careers on picking correctly.

When we've assembled the profiles and mined the group's collective wisdom, we'll put the results together for you in a special mid-2002 issue, which we think will be one of our most exciting packages yet.

We think the TR100 project is special in some of the same ways that our magazine as a whole is special. The project is upbeat about the future of technology, but at the same time firmly rooted in reality. It doesn't pretend to be more than it is or succumb to the latest fads and hype. At the same time, it provides a far better guide to the most important emerging trends in technology than just about any other source. Enjoy it—and, even better, participate by naming your favorite young innovator.

—John Benditt

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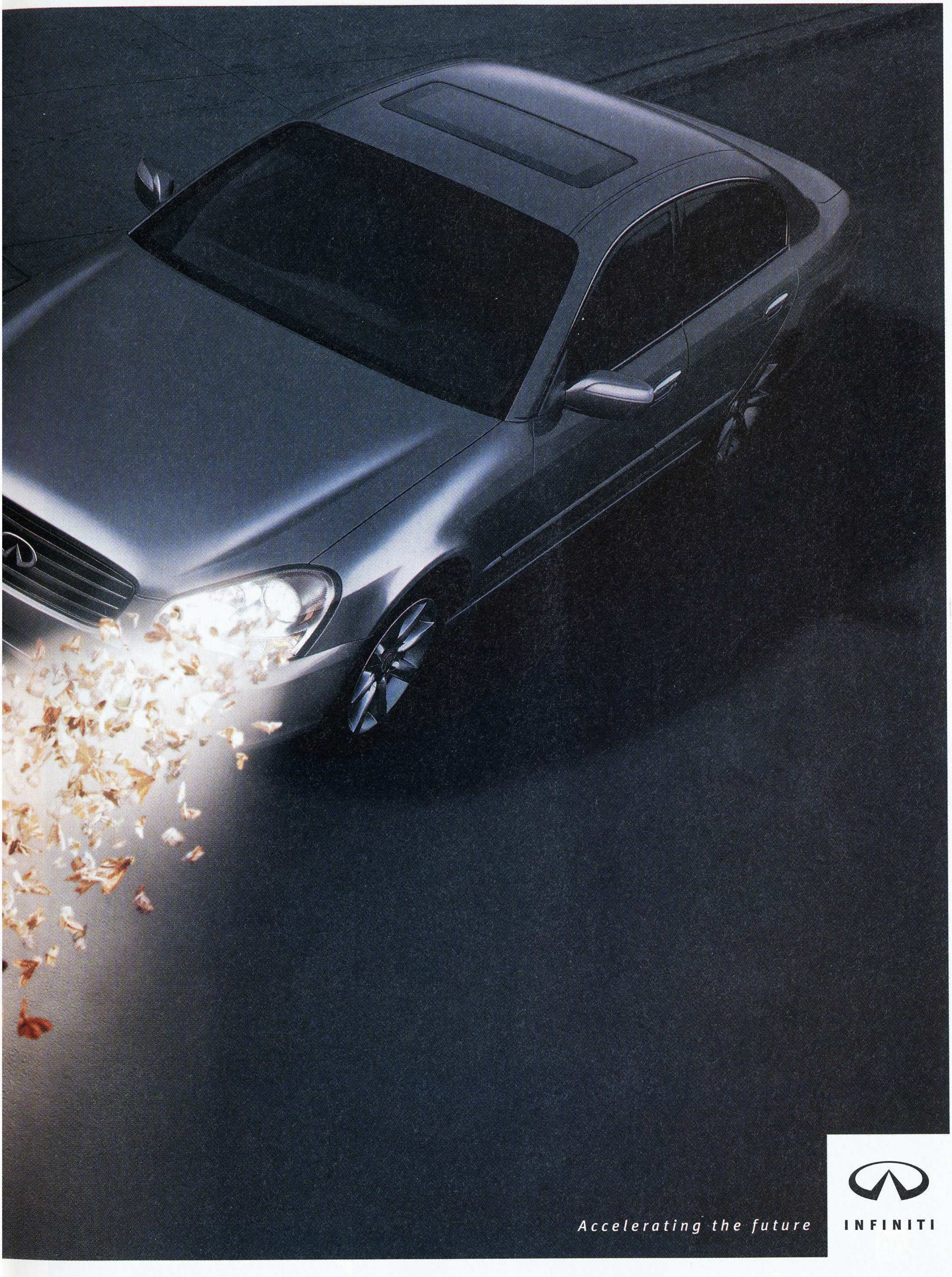
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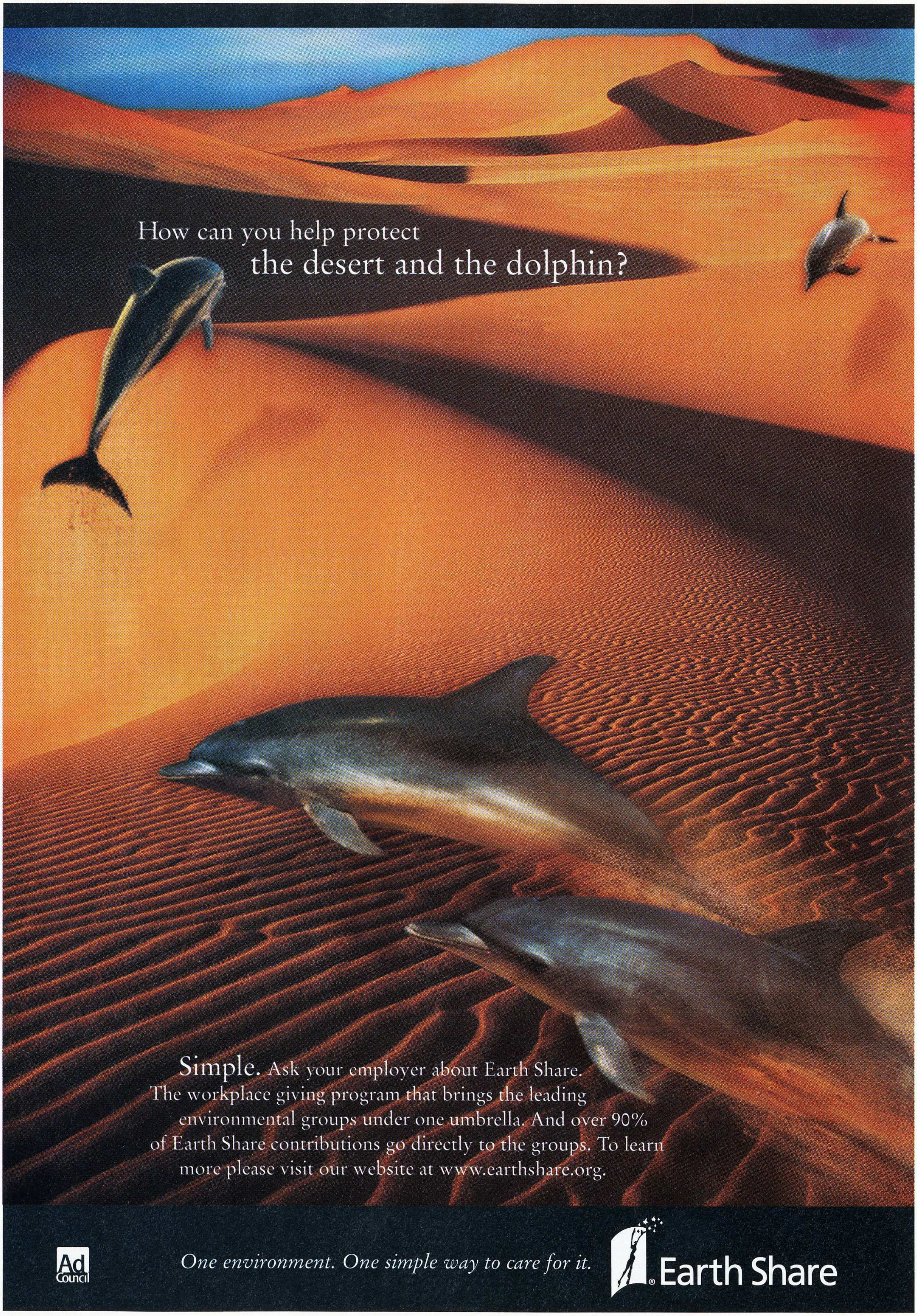
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> *"I would not want to be in an accident involving a vehicle using hydrogen, and I shudder to think of thousands of local 'hydrogen' stations."*

Not Sold on Hydrogen

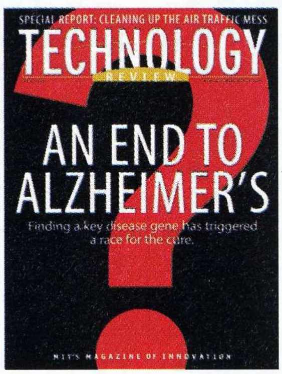
YOUR INNOVATION STORY "FUEL CELLS: A Lot of Hot Air?" (*TR* March 2001) gives me pause. Hydrogen under pressure is difficult to contain; leaks are difficult to detect, and you need to attain virtually zero leakage; it is explosive and highly flammable. Finally, if leaking hydrogen catches fire before it explodes, it burns with an invisible flame.

I would not want to be in an accident involving a vehicle carrying or using hydrogen under high pressure, and I shudder to think of thousands of local "hydrogen" stations. Gasoline, in contrast, is a relatively safe fuel.

Regarding economics and environmental issues, so many analyses of the energy efficiency and environmental impacts of various systems for powering vehicles do not address entire processes from beginning to end and come to less-than-realistic conclusions.

Lastly, one has only to have driven a Japanese hybrid gas/electric vehicle to be impressed with its simplicity and reliability. Hybrid systems require little change in our fuel infrastructure while leaving open the option for fuels other than gasoline that could power an internal-combustion/electric hybrid.

RICHARD LEWIS
Scarsdale, NY



REGARDING THE ARTICLE "FUEL CELLS: A Lot of Hot Air?", there are a number of defects in Malcolm Weiss's MIT study. First, it was paid for by four oil companies and Ford Motor. Second, the study focused on greenhouse gases and ignored pollutants. Third, the thrust of the study is somewhat skewed. When you read the small print, you find out that Weiss's estimate of the carbon dioxide emissions of a hypothetical internal-combustion engine developed in 2020 was an extrapolation based on the rate at which the industry has improved the efficiency of such engines; whereas he used the current efficiency of the fuel cell. Not what you would call rigor.

WALLACE BRAND
Washington, DC

AS A PATENT ATTORNEY WHO STAYS current with fuel-cell and hydrogen-production technologies, I must take issue with the conclusions drawn in your article "Fuel Cells: A Lot of Hot Air?" I have reviewed the MIT study referenced in your article. While I find it noteworthy, your article fails to mention the plenitude of disclaimers within that study. By its own terms, the study notes, "All our quantitative results are subject to...uncertainties... and those uncertainties are larger for rapidly developing technologies like fuel cells." The MIT study had a narrow scope and was not the indictment of fuel-cell technologies you paint it to be.

The study relied on dated hydrogen production technology. For example, hydrogen production from reformation of natural gas at the wellhead and reinjection of carbon dioxide into the well was not discussed, although it is a method that dramatically brings down the cost of hydrogen and vastly reduces the greenhouse gases produced. Nor did the study mention hydrogen production through electrolysis of water driven by electricity produced by wind, solar or hydropower, or a host of other low- or zero-greenhouse-gas-emitting hydrogen production technologies.

The study also ignored both the environmental and the societal costs of trying to maintain an oil economy, and the medical and health costs arising from gasoline additives like MTBE.

MARK KRIETZMAN
Sonnenschein Nath & Rosenthal
Los Angeles, CA

Malcolm Weiss responds:
Our study was designed to develop a consistent and comprehensive methodology for comparing automotive and fuel technologies that could be commercialized by 2020. Our many U.S. and European reviewers endorsed the final methodology. But neither they nor our readers necessarily agree with every specific technical assumption we made in applying the methodology.

The hydrogen production technology we assumed is the cheapest system (according to several independent assessments) that could be developed and deployed within 20 years to supply hydrogen to cars. All the technologies suggested by Mr. Krietzman would result in much greater costs of delivered hydrogen, although with high potential for reduced greenhouse gas emissions—as we specifically say in our conclusion about the future, 30 to 50 or more years from now.

The fuel-cell hybrid systems assumed in our study are all significantly superior in cost, weight and efficiency to the fuel-cell systems available today. Advocates may believe that even greater advances will be achieved. The combustion-engine hybrid systems assumed incorporate only advances in engine technology that are well grounded in current development efforts.

We welcome letters to the editor.
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E-mail: letters@technologyreview.com.
Please include your address, telephone number and e-mail address.
Letters may be edited for clarity and length.

Turbulence

ON READING "FLYING MADE EASY" (*TR* March 2001), I was aghast at the irresponsibility of both the writer and your editorial staff. Personal-use airplanes available to anyone who can afford a midrange BMW? Is David H. Freedman unaware of the hitches on the road to the nirvana promised by the last widely available personal-use vehicle—the automobile? What kind of gas mileage will these vehicles get? How far will the owners live from the central city? Ever heard of

sprawl? Loss of habitat? How expensive will it be to finance the infrastructure needed for this transformation? Not to mention extended sewer, water and electric service to reach the latest Levittown. And of course, more roadway to maintain, since the cleaning staff will still need to access these increasingly isolated enclaves of the rich.

Don't tell me it's not the mission of your magazine to address social issues. Would you present an article on wondrous improvements in electric-chair technology without mentioning the moral issues surrounding the death penalty?

CHARLOTTE BALTUS
Rochester, NY

AS A PRIVATE PILOT, I SHUDDER AT THE thought of sharing air space with dummies behind the controls of aircraft. I find it scary thinking that people who are unable to program a VCR, or refuse to be taught to stay out of the left lane on a highway except to pass, should be permitted to be in command of an airplane.

RON GAUDET
Cheshire, CT

I'VE JUST READ YOUR THREE ARTICLES about aviation advances and found them interesting and enjoyable.

However, as a person who has been flying general-aviation aircraft such as Cessnas and Pipers since 1959, I found David H. Freedman's claims that his 12-year-old son single-handedly landed a Piper Arrow quite smoothly and professionally on his very first try to be quite a stretch ("The Five-Minute Pilot," *TR* March 2001). I strongly suspect the MIT professor in the front seat was actually the person who had the hands-on control through the landing sequence.

While it is true that new avionics equipment will make navigation and other tasks such as avoidance of midair collisions much easier and more assured, the basic learned skills involved in landing an aircraft cannot be replaced with any type of equipment presently available, or even on the design boards, for general-aviation aircraft. Airline equipment simply does not exist today to allow a person of any age who has never done it before to safely conclude a landing as described in the article.

PETER MINGES
Cincinnati, OH

David H. Freedman responds:
As someone who had to work on landings for many hours to get his pilot's license, I can assure Mr. Minges that if I hadn't been on the plane myself, I would have shared in his skepticism. Bear in mind that my son was receiving a nonstop stream of detailed verbal instructions from an expert pilot who specializes in automating airplane control. And I suspect that my son's thousands of missions as a video-game warrior didn't hurt. The landing was indeed a smooth one.

New(d) Economy

YOUR PERCEPTIVE EDITORIAL "NEW(D) Economy" (*TR* March 2001) correctly questions the myth (or "drivel") of the "new economy," while it draws attention to the most fundamental question: "Will the new high-tech world tend to be better or worse than what we now have?" You point out (citing Dertouzos) that machines "exist to serve us, not the other way round." They are the means, not the ends. But what are the ends? There are very few signs that we are prepared to try to identify those ends, let alone commit to the considerable attention and hard work required to achieve them. We must establish constructs to ensure that the marvelous promise of new technologies outweighs the negative and frivolous uses that can accompany them. The task of identifying, organizing and implementing positive ends should begin now. Are we up to the job?

JAMES E. GANDER
Ottawa, Ontario

I CONCUR THAT THERE NEVER WAS A New(d) Economy separate and distinct from some other economy. New Economy visionaries overlooked the fact that the goods and services being consumed online originated in the "Old Economy." Many a dot com's demise can be attributed to its fixation with distribution infrastructure (a.k.a. the Web). CEOs spoke volumes of "business models" and little about their product or service offerings.

The fundamental tenet of business is that it must create value for its customers and be profitable. Companies who execute this strategy will be successful in any economy.

JOE LEANDRI
Wyoming, PA

Why Turn the Page?

I DON'T BUY CHARLES C. MANN'S POINT that "electronic paper could be so inexpensive that a few hundred sheets of it [could fit] in a book" ("Electronic Paper Turns the Page," *TR* March 2001). Clearly, cost will come down, but why bind a hundred sheets together? Digitally speaking, one sheet should be enough.

The real value of electronic paper will come from the ability to rapidly develop ideas through collaboration with others, using digitally "connected" sheets of electronic paper. The handiness of a single sheet can replace the expediency of the "idea on a dinner napkin."

ANDREW STEIN
St. Charles, IL

Understanding Alzheimer's

MY GRANDMOTHER STARTED SHOWING signs of Alzheimer's this year, so I'm interested in learning all I can about the disease. I have a few questions regarding "An End to Alzheimer's?" (*TR* March 2001).

1. In Alzheimer's sufferers, what causes the beta-secretase to replace the alpha-secretase? In other words, why does the beta-secretase spring into action before the alpha-secretase?

2. In a normal person, why doesn't the amyloid precursor protein that is cut off by the alpha-secretase become plaque buildup? Where does it go once it gets cut off by the alpha-secretase? What about the amyloid precursor protein that is cut off by the gamma-secretase?

3. Let's say that, in theory, you are able to block all of the secretases (alpha, beta, and gamma) from doing their jobs. Will the unrestricted growth of the amyloid precursor protein cause any problems? Do we know what the effect will be?

4. Finally, this question is in regards to the vaccine that is proposed by Dale Schenk. Will this simply remove plaque buildup that is already there? Will it have anything to do with blocking secretase? Will this simply stop future plaque buildup, or could it reverse the process and remove existing plaque buildup?

ERIC JEWELL
Dallas, TX

Ken Garber asked Alzheimer's researcher Dr. R. Scott Turner of the University of Michigan to respond. Here's his answer:

1. No one knows for sure why the beta-secretase springs into action before the alpha-secretase. It may have more to do with beta-secretase's target, amyloid precursor protein, than with the beta-secretase enzyme itself. In some inherited forms of Alzheimer's, amyloid precursor protein is altered in ways that seem to encourage creation of more of the beta-amyloid peptide that forms the harmful plaques. In noninherited cases, we're not sure if more beta-amyloid is formed or just that less is cleared from the aging brain.

2. Amyloid precursor protein has important functions in the body, and is continually made and broken down normally. It doesn't form plaques possibly because it's more soluble or doesn't aggregate as easily as the beta-amyloid fragment.

3. We're not sure that blocking all secretases would leave amyloid precursor protein growth unrestricted. (For some proteins there are feedback mechanisms in the cell to prevent this.) Anyway, blocking these enzymes would cause problems. Gamma-secretase is essential to life. As for alpha-secretase, you might actually want to increase its activity, since this should reduce beta-amyloid formation and inhibit plaque deposition.

4. As far as we know, the vaccine doesn't affect the secretase enzymes or beta-amyloid formation. It seems to work by preventing beta-amyloid deposition and by helping clear it from the brain. The vaccine does promote plaque reversal in mice, but works much better in prevention rather than treatment. Whether this works in humans, and whether (if it does) it can actually make Alzheimer's patients better, remains to be seen. Because amyloid plaques trigger other damaging processes in the brain, removing them in advanced Alzheimer's may not correct the disease. Human trials of vaccines are just beginning, and will require several years of testing before we know if they're safe and effective for prevention or treatment of Alzheimer's.

Editor's note: Sharp-eyed readers may have noticed that we've published letters related to the March 2001 issue two months in a row. That's because we're shifting our Feedback schedule to accommodate a larger selection of your letters. From now on, Feedback will refer not to the last issue but to the one before. The next Feedback will be on the April issue.

PROTOTYPE

STRAIGHT FROM THE LAB: TECHNOLOGY'S FIRST DRAFT

Diamond Chips

Silicon Valley may soon have to change its name. A team of scientists led by Matthias Schreck of the University of Augsburg in Germany has developed a crystalline diamond film that could produce more resilient semiconductor chips than those made from silicon. Until now, synthetic diamonds have proved a poor semiconducting material. Their microscopic crystals are a disorderly hodgepodge, and their edges are not evenly aligned, impeding the flow of current. Now, Schreck and his colleagues have discovered that by growing the diamond film on a surface of iridium, instead of on silicon, they can keep its grain boundaries aligned. Adding atoms of boron or nitrogen enables the diamond film to conduct electricity. Manufacturers plan to build a diamond chip that can withstand temperatures of 500 °C, compared to only about 150 °C for silicon chips. The chips would be most useful in devices located near hot-burning engines, such as those used in automobiles or airplanes.

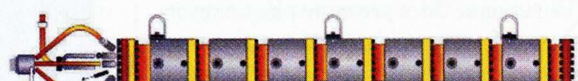
Edible Wraps

VITO ALUIA

With the increasing demand for healthy snacks, manufacturers are grappling with ways to package fruits and vegetables to keep them fresh longer. A new edible film fabricated by Tara McHugh of the U.S. Department of Agriculture's Agricultural Research Service in Albany, CA, might be the answer. Not only can the material extend the shelf life of fresh foods, preventing them from browning, but it also makes the packaging more recyclable. And if you're too lazy to walk to the recycling bin, you can even pop the plastic in your mouth and eat it. McHugh created the edible material from pureed fruits and vegetables, then dried it to form a thin sheet of opaque film. Future research plans include fortifying the film with tasty nutrients or adding lipids to make the packaging more water resistant. A number of food-processing companies have already expressed interest in the material, which could reach supermarket shelves within the year.

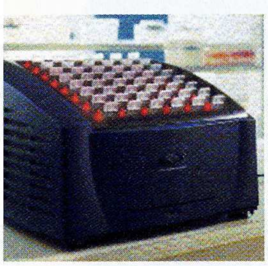
Rocket Power

The same technology that sent humans to the moon may soon be powering your home with cleanly produced electricity. Clean Energy Systems of Sacramento, CA, has developed a gas generator that combines rocket and steam turbine technology to generate power while emitting minimal pollutants. The system burns a mixture of hydrocarbons and oxygen in the presence of water; it releases no carbon monoxide or unburned hydrocarbons. Carbon dioxide is extracted from the water for storage instead of being released into the atmosphere. A small-scale unit was recently tested at the University of California, Davis; Clean Energy Systems is building a full-scale generator.



CES

Biotech Food Detector



MOTOROLA CLINICAL MICRO SENSORS

Genetically modified crops have quickly gone from farmer's best friend to profit killer. European countries have imposed strict limits on imports, and in the United States opponents are demanding better labeling. Yet tracking genetically modified foods through the distribution chain is difficult and expensive. To make it easier, Motorola's Clinical Micro Sensors unit and GeneScan Europe of Freiburg, Germany, have developed a portable gene detector. The prototype combines Motorola's eSensor DNA detection technology with GeneScan's collection of DNA probes. Users place a prepared sample in a matchbook-sized biochip cartridge that detects specific genes. The cartridge is then plugged into a toaster-sized reader controlled by a laptop computer. Motorola expects to ship the detector by year's end, and hopes to shrink the unit to a handheld device within three years.

Mixing Darks with Lights

Because most recycling centers don't accept dark-colored plastics, more than four billion kilograms of car bumpers, cell phones and other materials clog U.S. landfills each year. Black plastic could easily be recycled. The problem: the polymers used in different plastics are incompatible, and melting them together yields an unusable glop. But the conventional plastic-identification method of analyzing reflected laser light doesn't work well with black plastic, which chars under the bright beam.

SpectraCode of West Lafayette, IN, may have solved the problem. The key is a laser beam that hops around. The beam can be bright enough to produce an identifying signal rapidly; by dancing from point to point roughly every tenth of a second, it never dwells on one spot long enough to burn it. SpectraCode CEO Edward Grant expects the probe to be used in commercial products by early 2002.

Fun with Fluids

Ink-jet printers, flat-panel displays and biochips all require the precise placement of microscopic amounts of fluids, but getting fluids to go where you want takes a lot more than just asking nicely. Researchers at Philips Research Laboratories in Eindhoven, the Netherlands, have come up with a promising approach. Their "electrocapillary" system, which uses no moving parts, shuttles fluid quickly through tubes as narrow as 350 micrometers wide—roughly three times the width of a human hair.

The tubes are actually filled with two fluids, which repel each other: one fluid is electrically conductive while the other is insulating. The wall of the tube also repels the fluids, but it's lined with electrodes. When the electrodes are charged, the walls exert less force on the conducting fluid, which is squeezed up the tube by the greater force exerted by the insulating fluid. The fluid moves at several centimeters per second, which is about a hundred times faster than the speeds other electrical techniques deliver. A Philips group led by Menno Prins has demonstrated a network of thousands of such electrocapillaries, which they say could have applications in optical switching.

Pond Pills

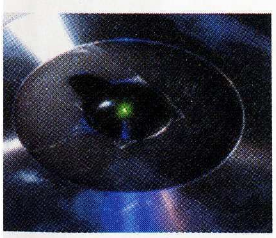
STONE

Wallowing in duckweed—a new source for drugs?

Protein-based drugs are big business, worth more than $17 billion a year. Genetically engineered bacteria and yeast efficiently churn out many protein pharmaceuticals, but as the proteins get more complex, the simple microbes sometimes fail. Drugmakers must then turn to increasingly expensive systems to make the proteins, which drives prices through the roof. Pittsboro, NC-based Biolex may have found an alternative: genetically engineer duckweed, a flowering pond plant, to secrete human proteins. The tiny plants grow very rapidly in a simple nutrient solution—doubling in population every 36 hours—and contain exceptionally large amounts of proteins. Biolex has proved the plants can do the work by using them to make complex therapeutic proteins such as interferons, which are used to treat some forms of cancer and hepatitis. The company is tweaking the system to increase efficiency and says that duckweed-produced drugs could be ready for testing in two to four years.

Nano Storage

In the world of computer data storage, it's all about making the digital bits occupy the smallest possible space. Researchers at the Georgia Institute of Technology have brought the concept to a whole new level—the nanoscale. By shining a blue laser beam onto an ultrathin film of silver oxide, a team led by Robert M. Dickson has created silver nanoclusters made up of only two to eight atoms each. Bits that small could give rise to optical discs holding thousands of gigabytes; today's best DVDs hold less than 10 gigabytes per side. The data is read by exposing the clusters to green light, causing them to fluoresce. Each cluster can be made to glow in a range of colors—not just the "on" and "off" of binary systems—opening the possibility of storing multiple bits in the same cluster simultaneously. So far, Dickson's group has used the fluorescent method to create nanoscale geometric images, such as the letter "L." Development of the technique for digital data storage will require further research to reveal why the material works as it does. One unresolved question: can the film be optically erased and rewritten?



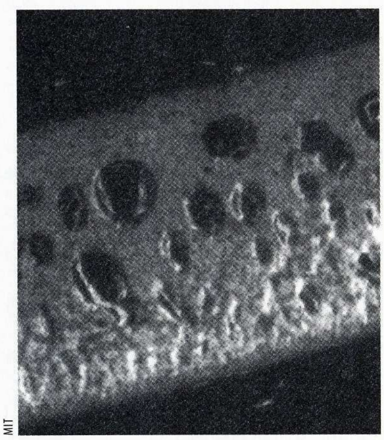
GEORGIA TECH

A cluster of silver atoms glows green.

Waste Not, Want Not

What do wastewater treatment and tissue engineering have in common? Not much, on the surface. Yet, in a remarkable feat of technological connectivity, MIT researchers have developed a new membrane that can serve both needs. Membrane-based filtration systems are a simple and effective way to remove solid materials from water, but because the pores are easily clogged, maintenance costs are high. MIT researchers led by polymer physicist Anne Mayes have created a membrane that includes a "comb" polymer at its surface. The polymer's two-nanometer-long bristles attract water molecules, which create a barrier against pore-clogging oils and proteins.

Mayes's team has also created a version of the polymer with biological molecules attached to the bristles to attract specific types of cells; such a material could be used to create artificial tissue for wound-healing and other applications. MIT is in the process of licensing both technologies.



MIT

Double-duty polymer membrane.

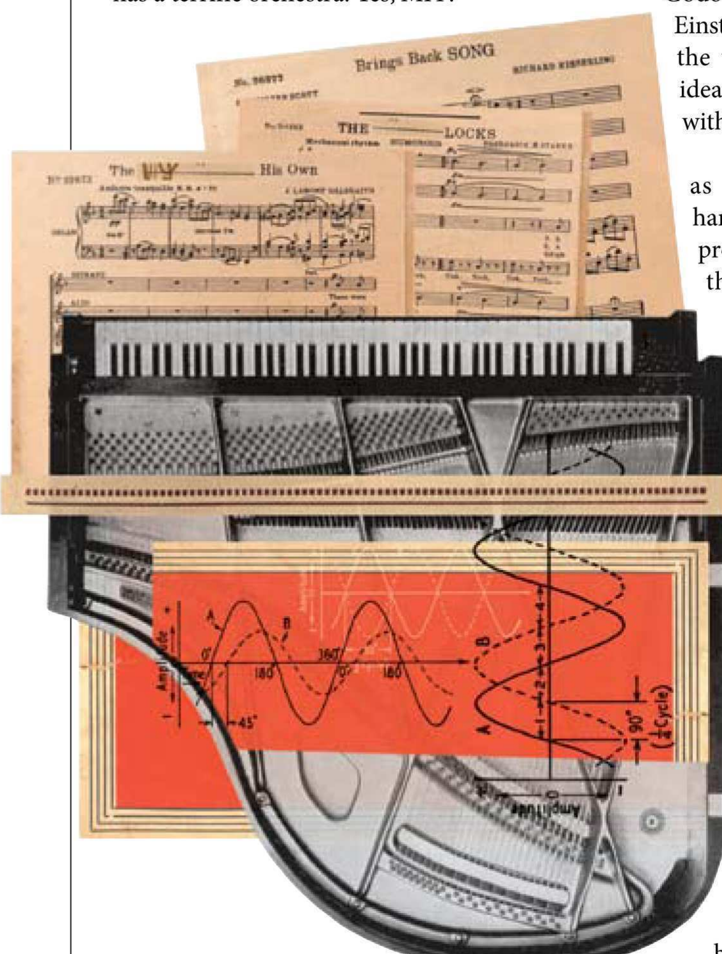
Scratch-n-Spin

For years, computer makers have been sniffing around the idea of delivering smells to consumers through their PCs. A device invented at the Illinois Institute of Technology may bring that promise home by embedding aroma-bearing chemicals on a CD-style disk. A laser in a special "Tele-Aroma Drive" heats the precise spot where an odor is stored, and a fan blows the released aroma toward a user's nostrils.

Existing smell makers create about 100 different aromas by opening scent-storage cartridges in various combinations. Chemical engineer Hamid Arastoopour says CDs beat cartridges by a nose. The CD aroma drives are "compact, you can put thousands of ingredients on them and easily send them out to people," he says. Disk-based catalogues containing a tantalizing whiff of faux Chanel No. 5 or a musky cabernet could land in mailboxes this year. Eventually, Arastoopour says, aroma disks could be integrated with DVD flicks. Smell-o-vision, anyone?

Playing by Heart

IT CAME AND WENT ALMOST without notice: a small musicale at Rockefeller University last winter that was part of a symposium called "Meet the Polymaths." Ten amateur pianists performed favorite pieces, playing by heart for the most part, and afterwards engaged in a panel discussion on ways that music and the sciences seem to go hand in hand. The correlation is striking. It is hard to find great scientists or technologists who don't have some flair or at least passion for music. Einstein played the violin. Artificial intelligence guru Marvin Minsky loves to play fugues. Claude Shannon, the recently deceased father of modern information theory, tried to make computers compose music. MIT has a terrific orchestra. Yes, *MIT*.



JASON HOWARD STATTS

Actually, the *New York Times* did notice the concert—where I was, incidentally, among the participants. Reviewing the event (in the paper's science pages, naturally), Bruce Schechter hit the nail on the head by including the following anecdote.

Two of the most towering piano virtuosos of all time, Josef Hofmann and Leopold Godowsky, were schmoozing at a party. Aside from being phenomenal pianists, the pair had something else in common: both were very short in stature, with remarkably small hands to match. After reverently shaking hands with the pianists, a fan was struck by their tiny hands. "How can you great artists play the piano so magnificently with such small hands?" she asked. Godowsky (a good friend of Einstein's) replied, "Where in the world did you get the idea that we play the piano with our hands?"

I'll second that. Now, as it happens, my own hands are better sized for pro basketball, but I play the piano passably. My piano duet partner, Mary Farbood, has rather small hands. We're proof that, in piano playing, size really doesn't matter. Godowsky was right: the piano is not just a tool for the fingers. Mind and heart matter a lot more.

Like all great artistic instruments—a paintbrush, pen and ink, a violin—the piano is a tool. It is a piece of technology. It has adapted over the centuries to fit the hands beautifully, but it is primarily a tool for expressing and exploring emotions, not finger exercises. And more than any other musical instrument, the piano is a universal channel. Almost any kind of music can be adapted to it. It is an SUV for touring through a wealth of literature, an amplifier of creativity. Yet in today's world of technological plenty—with infinite channels, disks and downloads, and with all the world's music increasingly available with a point and a click—it is easy to lose track of what makes music making so vital and so deeply humane.

Suppose you're in the audience at Carnegie Hall. At 8:07 p.m., the house lights dim. The stage lights brighten. The audience hushes, then bursts into a thrill of applause as a performer in concert dress strides onto the stage toward a large instrument. Bowing warmly, the soloist pulls a silvery disc out of a pocket, slips it into a slot, pushes a big red button and sits down. Everyone listens intently to a perfect recording.

Yawn.

This scenario is not hypothetical. Such automated "performances" are common in avant-garde computer-music circles. Progress in music certainly didn't stop with pure, unaccompanied Gregorian chant. At clubs, deejays who spin or scratch vinyl albums are more common than live bands. There's a vast armamentarium of technologies that mediate between performers and listeners, bridging gaps of time and space. And Glenn Gould, the reclusive pianist who famously abandoned live concerts in favor of perfection in the recording studio, might have approved. But he was an outlier. The best recording is like the memory of a kiss: something important is missing. Even in this era of MTV and the Internet, going to Carnegie Hall to hear someone play a CD seems like a pretty stale experience. It hardly compares to the thrill of watching Vladimir Horowitz or Art Tatum rip into a piano—or hearing Segovia turn a guitar into poetry. Or even watching Pete

Townshend smash one. And yet, this scenario captures the difference between musical experiences of the not-so-distant past and those of today. In the 19th century, living rooms were live-music rooms. They were places where people made music. No longer.

With infinite channels, disks and downloads, with all the world's music increasingly available with a point and a click, it is easy to lose track of what makes music so vital and so deeply humane.

The piano was a pretty high-tech machine for 1850. And I mean that "pretty" literally. It merged elegantly with beautiful furniture and became a staple of gracious living. Everyone had a piano. (Computers are on a slow path to domestication, provided your furniture is "strawberry" or "lime" or "titanium.") Of course, it hardly seems like technology anymore. Personal computing pioneer Alan Kay once quipped that technology is anything that was invented after you were 25. Nevertheless, the piano was still a bit like the Internet of the 19th century. It was the home stereo/TV. It was a prominent social hub in the family room, the glue that drew society together. Instead of downloadable MP3s and Monday Night Football, one had a piano. Printed score sheets were the interactive software of the 19th century: Liszt's transcriptions of Wagner, or Brahms's duet versions of his own symphonies, made for a great evening's entertainment.

Like a computer, the piano invites nimble fingers and a lot of mental dexterity. But unlike a computer, the piano requires you to put a lot into it to get much out. In the words of MIT's Seymour Papert, this is "hard" play, as opposed to the easy play of pushing a button to hear a recording. Hard play builds self-esteem. You might be learning to cook, practicing figure skating, finishing a crossword puzzle or playing a musical instrument. All of those pursuits are so deeply satisfying because they are hard: mastery of them requires close attention and repeated practice. The more you do them, the better you get, the better you feel about yourself—and the better everyone else around you feels. Would you rather watch a friend or a child play a video game, or play music?

That cliché about how learning a foreign language deepens one's grasp of one's native tongue really is true. And music, which comes in so many dialects and cultures, which moves through us with its strange, special air, is the language of emotion. Author Michael Crichton once said that taking the time and applying the discipline to write was the best way he knew to really connect with life's experiences. In precisely the same way, studying music is a rewarding way to map human emotions.

I am by no means a professional musician. I'm an amateur. And love, as Einstein used to say, is a better master than duty. But I've always felt that English was my second language. Music is my first language.

Actually, music is everyone's first language: it is the way we learn how to share our strongest feelings—feelings that begin in the gut, that we shape into sounds in ways that transcend words. Everyone responds to music in some way. Yet nobody really knows why. And it is no accident that so many of our most powerful and expressive life experiences are always accompanied by music. There are processionals at weddings, requiems at funerals, marching bands on the Fourth of July, carols at Christmas, lullabies for babies, national anthems at ball games, soundtracks for movies, and show tunes on Broadway. It is hard to find a powerful cultural experience that *doesn't* have music woven into it. Even when you can't hear it, music seems to accompany the best expressions of humanity. Bart Giamatti of Yale University used to say that all the noise that pours forth from universities—all the lectures, debates, classes, protests, all of that brouhaha—is perhaps, in the end, the music of civilization.

One of the things I especially like about the piano is the way it challenges both hands and brain, working both to the limit, and in a balanced way. All those fantastic physical and mental challenges frame the emotional message. Beyond the piano, that same sense of balance, of proportion, between the work of body and mind is vital to shaping a fulfilling life.

In thinking about what music adds to our lives, and in wondering how future technology might deepen our enjoyment of it, it might help to recall a bit of wisdom from the ancient Greeks. After all, they weren't so different from us. They just weren't as confused by so many dizzying technologies and ideas. Socrates summed it up cogently in the third book of Plato's *Republic*: "There are two arts which I would say some god gave to mankind: music and gymnastics, for the service of the high-spirited and the love of knowledge in them—not for the soul and body incidentally, but for the harmonious adjustment of these two principles by the proper degree of tension and relaxation of each."

Spectacular arrays of technologies and experiences will be ever more available to help us connect with the music we love. It's the food of love, after all, and our appetite for it is insatiable. But the lesson here, and the piano is a humble reminder, is that the best joy in music lies in making it. That is why, in the longer view, "easy" listening technologies (recordings, computer networks) will be taken for granted. We do show signs of growing out of the all-consumption all-the-time phase of our technical and cultural evolution. Interactive, communicative, sharable, engaging and expressive technologies are on the rise. And technologies that aim at the "hard" end of the spectrum of play—creative tools like pianos, and information tools that engage not just the mind and the fingertips, like today's computers, but also the body and the soul—those are tools to cherish. ◊

INNOVATION

THE FOREFRONT OF EMERGING TECHNOLOGY, R&D AND MARKET TRENDS

BRIAN CAIRNS

A Donor Named Wilbur

Pig-to-human transplants could become standard practice in just a few years

MEDICINE | The numbers are grim. According to the United Network for Organ Sharing, more than three times as many people in the United States were waiting for heart, kidney and liver transplants than received them in 1999; over 5,500 people died waiting for organs. And many more patients could benefit from organ transplants than ever make the waiting list, either because they are too sick or too healthy to qualify. According to one estimate, 45,000 Americans could benefit each year from heart transplants, but only 2,000 or so human hearts are available.

One promising solution to this medical predicament is to harvest organs from suitable animals and use them for human transplant. It may sound outlandish, but several biotech and pharmaceutical heavyweights, as well as some smaller biotech firms, are gearing up to do just that *(see table, next page)*. In preliminary experiments, these companies have already implanted animal cells in human volunteers to treat such diseases as Parkinson's and epilepsy. Researchers plan to start whole-organ clinical trials in the next two to three years.

The use of animal organs in human transplants is not exactly new. You may remember "Baby Fae," the 12-day-old California infant who, in 1984, received a heart transplant from a most unusual donor—a baby baboon. This controversial experiment marked the first time most people had ever heard of "xenotransplantation," transplanting tissues or organs between species, and Baby Fae's very public death only 20 days after her surgery chilled the climate for xenotransplantation work. Still, medical researchers quietly pressed ahead, and their efforts may soon pay off.

The animal of choice in the new generation of experiments? Pigs. That's because pigs are both plentiful and easy to raise, and "the similarities to man are amazing," says Julia Greenstein, CEO of Immerge BioTherapeutics, a joint venture between Swiss drug giant Novartis and Charlestown, MA-based BioTransplant.

But transplanting tissues from pigs to people does present a few problems. The most critical is "hyperacute rejection," an immune reaction that causes organs from pigs to turn black and cease functioning within minutes of transplant into humans. The cause of this reaction is a sugar called alpha-gal that laces the surface of every pig cell. Since human cells don't make this sugar, the immune system produces antibodies against it and kills all cells bearing it.

For whole-organ transplants to become reality, a strategy is needed to deal

with the troublesome sugar. That's why companies such as Princeton, NJ-based Nextran are genetically engineering pigs to make proteins that help repress the immune reaction that the sugar causes. Nextran, owned by pharmaceutical giant Baxter, has already used the livers of such pigs to keep patients with acute liver failure alive until donor organs were found. In these early human tests, the pig livers remained outside the body, but "it's just a prelude to going into a human," says University of Pittsburgh transplant surgeon John Fung. The company plans to apply for permission to conduct preliminary human trials of such xenotransplants by the end of next year.

Other companies, including Immerge, PPL Therapeutics and Advanced Cell Technology, are combining this strategy with efforts to completely eliminate the guilty pig sugar. To do this, they must "knock out"—disable or remove entirely—the gene for the enzyme that makes the sugar. There is some concern, however, over whether pigs can survive without the sugar. "Chances are the pigs will be healthy, but no one's 100 percent sure," says immunologist David Cooper of Massachusetts General Hospital's Transplantation Biology Research Center.

Even if the pigs do survive, genetic modifications alone might not be enough to conquer transplant rejection problems, even with antirejection drugs. So PPL, Immerge and Advanced Cell Technology are pursuing additional strategies for blocking rejection. Each hopes to fool the human immune system into thinking that a new pig organ belongs in the body, usually by infusing or implanting pig bone-marrow cells into the recipient several weeks before a transplant operation. The idea is to use antirejection drugs to keep the marrow cells alive long enough for the human immune system to start thinking of the pig cells as "self"—reducing the patient's dependence on very large doses of the powerful drugs after the organ transplant. Fung is skeptical, though: "Trying to get animal organs to be accepted using approaches that haven't worked in human organ transplantation requires a leap of faith."

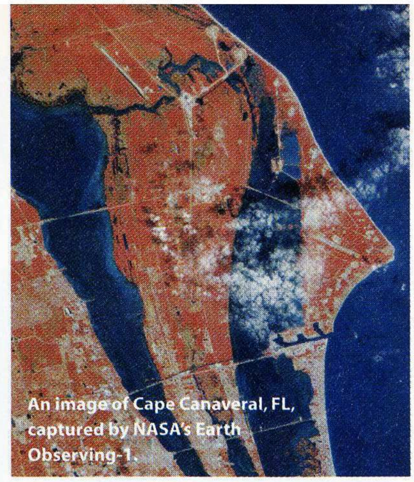
Omaha, NE-based Ximerex is even more ambitious, trying to completely eliminate the need for antirejection drugs by "introducing" individual pigs and transplant recipients prior to surgery. A patient's bone marrow cells would be infused into a pig fetus, educating both the pig and human immune cells to think of each other as self. After the pig's birth, hybrid pig/human bone marrow would be put back into the patient. One drawback: patients would have to wait four to five months between bone marrow sampling and transplant operations. Ximerex president William Beschorner doesn't think the obstacle is insurmountable: "The typical wait for a human transplant is well over a year. It would not be a major problem for most patients."

Each of these companies hopes to begin clinical testing of heart and kidney xenotransplants in the next few years. Although Cooper is generally optimistic, he sounds a note of caution. "It's like peeling an onion: every time you pull off one layer, you find another problem underneath." The thousands who die each year waiting for new organs hope those problems are solved soon.

—**Erika Jonietz**

Xenotransplantation Companies

COMPANY	LOCATION	PROJECTS
Advanced Cell Technology	Worcester, MA	Kidney, heart
Alexion Pharmaceuticals	New Haven, CT	Nerve-cell-based therapies
Circe Biomedical	Waltham, MA	Liver, pancreas
Diacrin	Charlestown, MA	Nerve-, liver- and retina-cell-based therapies
Immerge BioTherapeutics	Charlestown, MA	Kidney, heart
Nextran/Baxter	Princeton, NJ/ Deerfield, IL	Liver
PPL Therapeutics	Edinburgh, Scotland	Kidney, heart
Ximerex	Omaha, NE	Kidney, heart, liver



An image of Cape Canaveral, FL, captured by NASA's Earth Observing-1.

COURTESY OF MIT'S LINCOLN LABORATORY

New Sky Eye

SPACE | Images from NASA's "Landsat" series of satellites have provoked awe and dismay for 29 years. The satellites—the nation's chief source of earth surface images—have revealed previously undetected earthquake faults, rain forest destruction and the melting of polar ice caps.

Future images promise to reveal even more. Last November, NASA launched a next-generation prototype satellite, Earth Observing-1, which carries test versions of instruments up to ten times better at detecting subtle differences in brightness and 25 times better at detecting colors. The first images are now in hand, and the space agency says the imagers show promise as a replacement to Landsat's 1970s-era equipment. Says NASA mission scientist Stephen Ungar, "It is conclusively proved that this technology works."

Earth Observing-1 "sees more crisply in a package that is cheaper and lighter," says physicist Don Lencioni, who helped develop one of the satellite's three land-imaging instruments at MIT's Lincoln Laboratory in Lexington, MA. In black-and-white mode, the new system can resolve features as small as 10 meters wide, instead of the old 15 meters.

This improved vision should allow for better monitoring of ocean pollution and crop health. And because the new satellite costs less than half of a Landsat, it could be feasible to send more than one into orbit. This would allow for more frequent checks on events like forest fires; Landsat images the planet only once every 16 days.

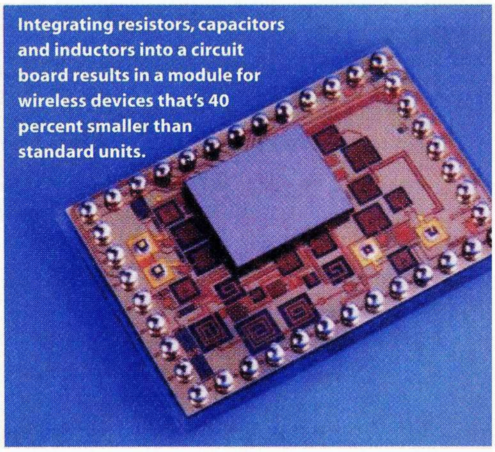
—David Talbot

Shrinking the Circuit Board

HARDWARE | Over the last 35 years, the transistors that make up computer chips have steadily shrunk, leading to smaller, faster and cheaper PCs. But while transistors perform the chip's computations, they can't do their work without other key electronic components—the resistors, capacitors and inductors that store and route power across circuit boards. Typically plunked down on the surface of a circuit board, these components have hardly shrunk over time, and they hog prime computing real estate—like a parking lot in downtown Manhattan. This places severe limits on how much smaller cell phones, personal digital assistants and computers can be made.

Several companies are now on the verge of breaking these limits by shrinking the components and integrating or embedding them into the circuit board to make computers even smaller. Others pack the miniaturized components together with microchips, then attach those combined units to the board. Manufacturers could soon shrink circuit boards to fit into smaller devices or fit more chips onto a circuit board. With close to 100 integrated components set to launch by year's end, cell phones may be a step closer to playing MP3s, Web browsing and acting as organizers all at once.

Key to making this happen has been the integration of power storage devices called capacitors. Fayetteville, AR-based Integral Wave Technologies has accomplished that with photolithography—the technique used to pattern the tiny silicon transistors on microchips. The company targets products to high-end computer chip makers and what firm president Michael Yates calls the "shrink-and-cram" market: wireless- and handheld-computer manufacturers. Other companies, like Intarsia in Fremont, CA, and Lucent Technologies spinoff SyChip, are also aiming products at the wireless market.


Integrating resistors, capacitors and inductors into a circuit board results in a module for wireless devices that's 40 percent smaller than standard units.

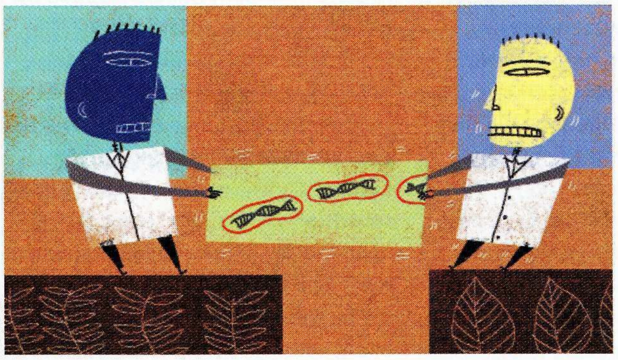
COURTESY OF INTARSIA

"Everyone knows we're going to integration," says University of Arkansas electronics researcher Richard Ulrich, who works for Integral Wave. "We're just trying to figure out the materials and how." Within three to six years, the technology could play a major role in creating multitasking cell phones and handheld computers with the same capabilities as today's laptop. **—Erika Jonietz**

Seed Spat

AG BIOTECH | Over the past two decades, genetically modified plants have graduated from laboratory curiosities to crops planted on millions of hectares. But while major seed firms have struggled with public worries over environmental questions and food safety, they've also been locked in a more private fight over a central question: who owns one of the industry's principal gene-insertion technologies?

The dispute is coming to a head. Last year, the U.S. Patent and Trademark Office issued a broad patent to Washington University in St. Louis covering one of the industry's most basic tools: the use of a soil bacterium to insert desired genes into the DNA of broad-leafed crops like soybean, cotton, potato and canola, conferring traits like herbicide tolerance and pest resistance. "That was the fundamental feature of our work," says Andrew Binns, a professor at the University of Pennsylvania and one of the inventors named on the patent. "It is the basis for practically all plant genetic engineering these days."



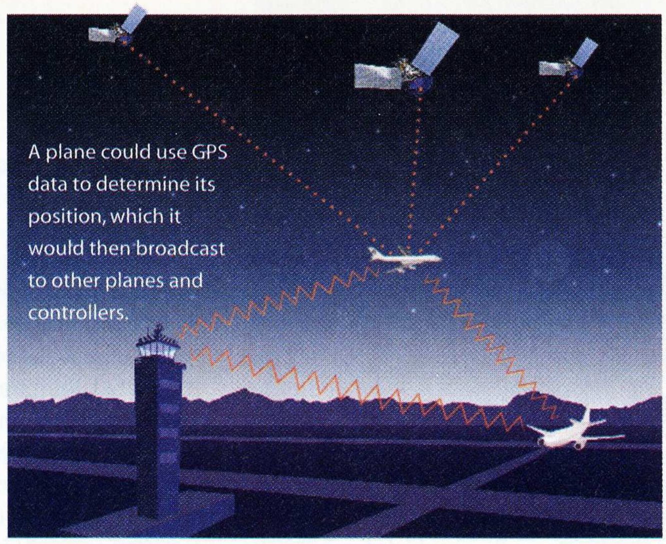
JAMES YANG

Agricultural biotech giant Syngenta, based in Basel, Switzerland, holds exclusive rights to the Washington University patent. Andrew Neighbour, director of the school's technology transfer office, says the patent "certainly provides [Syngenta] with a strong position in the marketplace." But while the granting of the patent was a watershed event—coming 17 years after its first version was filed—the issued patent is a shadow of its original self. Many of the claims originally filed are absent; these are still in dispute.

Syngenta isn't the only seed company interested in the patent's fate: Monsanto, Pioneer and Dow AgroSciences also make heavy use of the technique. Syngenta says it is not yet trying to collect royalties on its patent. And none of the companies would comment on the claims being fought out in the patent office, what the technology is worth, or what the financial impact might be once ownership is resolved. The patent office could rule as early as next year. But given the technology's key role in a multibillion-dollar industry, the next stop may well be the courts. —Alexandra Stikeman

Precision Approach

Boeing launches satellite air-traffic pitch



BETSY HAYES

AIR TRAFFIC | Air travel delays are bad and promise to get worse; the Federal Aviation Administration's current "build a little, test a little" strategy for air traffic control modernization isn't expected to keep pace with exploding long-term passenger demand. Now Boeing is throwing its corporate might behind a more ambitious technological overhaul: a new air traffic control infrastructure based on satellite tracking rather than radar. Boeing CEO Philip M. Condit first floated the idea in January; the company plans to publicly flesh out the details this month.

In theory, tools based on satellite-derived Global Positioning System data can increase air traffic capacity, says Carl McCullough, an FAA director. "The really precise information that only GPS can give you allows reduced separation between aircraft and more direct routes," he says. And the FAA is building a nationwide system for refining and verifying GPS signals to allow satellite-based instrument approaches at thousands of small and medium-sized airports.

Satellite-based air traffic control is already being used in places as far-flung as Australia, Mongolia and parts of Alaska—regions with little or no radar coverage. In addition, the air cargo industry is testing satellite tools and datalinks to speed overnight sorting operations by compressing takeoffs and landings.

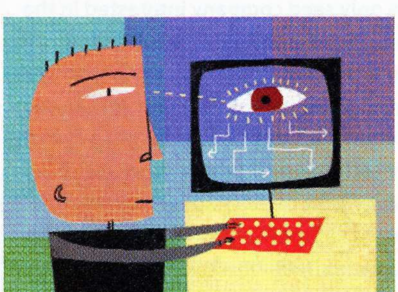
But around congested cities, satellite information and aircraft datalinks can't be relied upon for collision avoidance and spacing unless every airplane—from jumbo jet to Cessna—is retrofitted with relatively expensive new gear. Even then, the advantages over radar at busy airports aren't evident, says Raymond LaFrey, manager of air traffic control programs at MIT's Lincoln Laboratory in Lexington, MA, which does research for the FAA. "I'm sort of puzzled by this announcement," LaFrey says. "Phil Condit is a very savvy guy, and he's a good plane builder. But I don't know what they are thinking of, and I don't think anyone else does, either."

However, Joe Platzner, a Boeing air-traffic management director, says the aerospace giant is "committed to spending a lot of money, a lot of people, a lot of research and a lot of engineering effort to make sure the system will have the capability, safety, and affordability we need." Platzner says the company's first job is to make air-traffic overhaul "a public policy priority." After that, the solutions will require more organization than innovation. "The more important thing," Platzner says, "is taking technology that exists, and doing large-scale system integration."—**David Talbot**

Behind BlueEyes

SOFTWARE | Most of us hardly notice the surveillance cameras watching over the grocery store or the bank. But lately those lenses have been looking for far more than shoplifters.

Engineers at IBM's Almaden Research Center in San Jose, CA, report that a number of large retailers have implemented surveillance systems that record and interpret customer movements, using software from Almaden's BlueEyes research project. BlueEyes is developing ways for computers to anticipate users' wants by gathering video data on eye movement and facial expression. Your gaze might rest on a Web site heading, for example, and that would prompt your computer to find similar links and to call them up in a new window. But the first practical use for the research turns out to be snooping on shoppers.



JAMES YANG

BlueEyes software makes sense of what the cameras see to answer key questions for retailers, including, How many shoppers ignored a promotion? How many stopped? How long did they stay? Did their faces register boredom or delight? How many reached for the item and put it in their shopping carts? BlueEyes works by tracking pupil, eyebrow and mouth movement. When monitoring pupils, the system uses a camera and two infrared light sources placed inside the product display. One light source is aligned with the camera's focus; the other is slightly off axis. When the eye looks into the camera-aligned light, the pupil appears bright to the sensor, and the software registers the customer's attention.

BlueEyes has set off warning bells at the American Civil Liberties Union. "Soon you won't only be able to capture how many people stopped by, but who they were," says Barry Steinhardt, associate director of the ACLU. "Once identity is established it will be cross-referenced to capture that person's income and buying preferences. It's only a matter of time." Not surprisingly, IBM's retail customers unanimously requested that the firm not reveal their names to the press, or the locations where BlueEyes has been implemented. —Claire Tristram

Calling All PCs

Home computers help to find a cure for disease

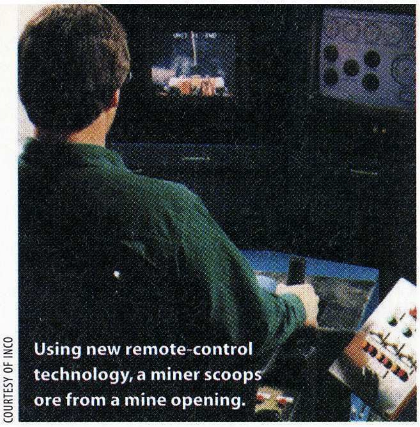
BIOTECH | You leave your computer hooked up to the Internet to go make a sandwich, and in your absence your computer engages in a bit of cancer research. Sound absurd? Actually, thousands of home computers today are being tapped to do research, helping biologists process gigabytes of data on genes and proteins. Now anyone with a PC and a modem can take part in solving some of today's major health problems.

The majority of the world's 300 million personal computers that are hooked up to the Internet waste most of their time sitting idle. To harness this unused power, researchers are using a system called distributed computing *(see "5 Patents to Watch: Collective Computing," p. 42)*. It divides large projects into many smaller tasks and apportions them to individual computers registered to take part in the project and already loaded with special software. The software crunches numbers either when a screen saver comes on or during the minute pauses between keyboard punches. The computers process the tasks and automatically transmit the results back to a central server for analysis. SETI@home, the University of California, Berkeley-based search for alien life, is one of the best known examples of distributed computing. But now the strategy is not only being used to look for ET; biologists are using it to tackle some of medicine's toughest jobs.

RESEARCH GROUP	PROJECT
Scripps Research Institute	Anti-HIV drug design
Stanford University	Protein folding, protein design
University of Oxford	Cancer drug discovery
National Cancer Institute	Gene expression data analysis
University of Maryland	Protein folding
Washington University	Gene sequence analysis

With these systems, researchers can perform large computations in a fraction of the time it used to take, without buying a $100 million supercomputer. Stanford University chemist Vijay Pande has launched Folding@home, a program that simulates the way proteins self-assemble or "fold" into a three-dimensional shape. Such simulations take immense computational power, but they're worth it: knowing how a protein folds is key to understanding a number of ailments like mad cow disease and cystic fibrosis, which are believed to result when proteins misfold. Pande's group is folding an intestinal protein, which assembles in 10,000 nanoseconds. "On a typical computer, you could probably do a nanosecond a day," says Pande. But with distributed computing, he can simulate the folding in as little as two months instead of 27 years, allowing him to do experiments that otherwise would be impossible.

Other efforts are springing up. For instance, San Diego, CA-based Entropia runs FightAIDS@home for the Scripps Research Institute; the program helps researchers look for new AIDS drugs to combat drug-resistant HIV strains. Fairfax, VA-based Parabon is working with the National Cancer Institute to analyze results from gene experiments. And United Devices, a distributed computing firm based in Austin, TX, is looking to get at least a million PC users to help University of Oxford researchers make steps toward finding a cure for cancer—a task that will take 24 million hours of computer time to accomplish. With this technology, a new generation of "researchers," from high school students to small-business owners, will be helping to do the hard work behind future medical discoveries. **—Alexandra Stikeman**



COURTESY OF INCO

Using new remote-control technology, a miner scoops ore from a mine opening.

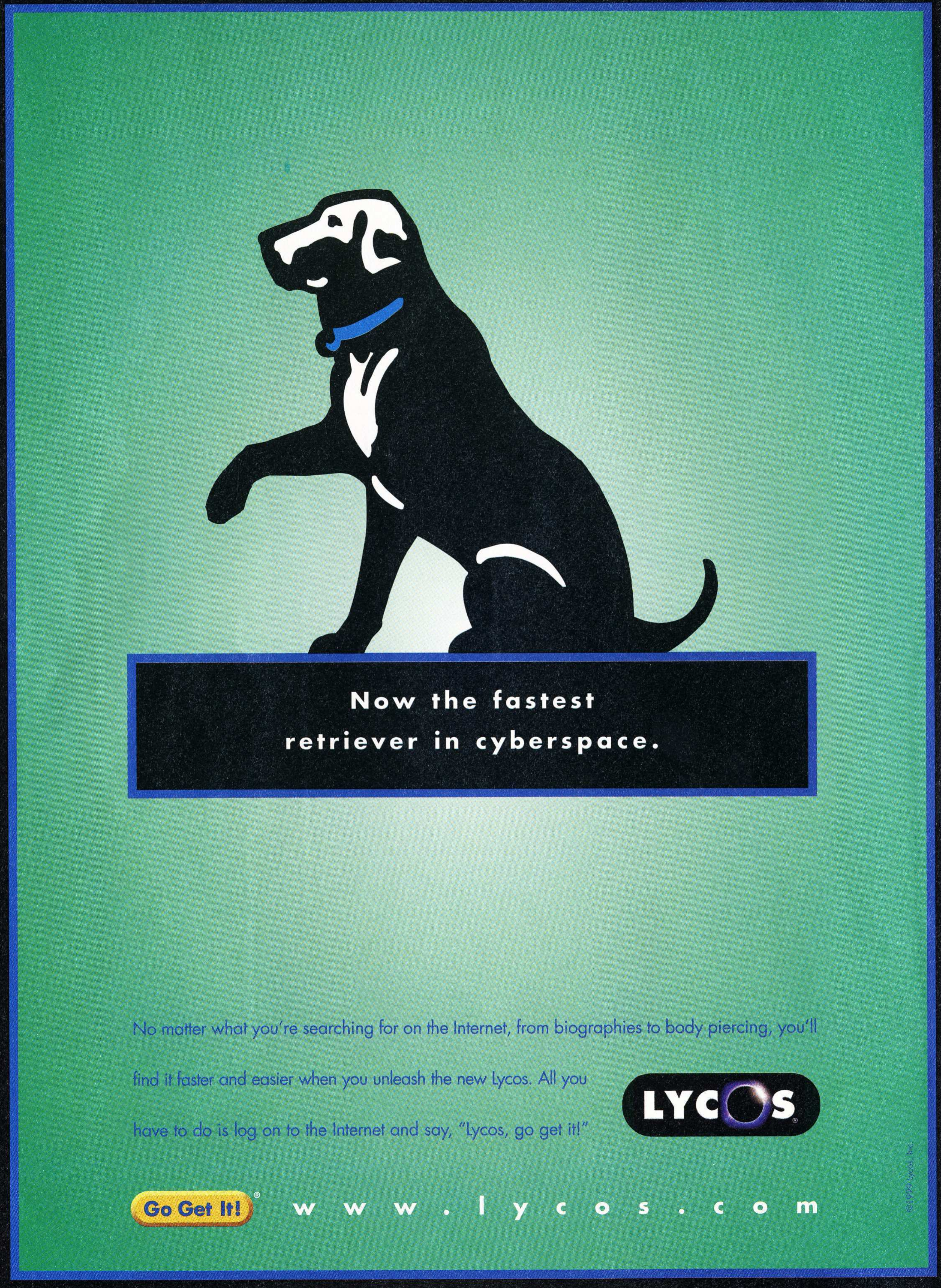
Robomining

ROBOTICS | **Underground mining may have become a bit safer with the completion this March of a mining automation project in Copper Cliff, Ontario. A consortium including Toronto-based nickel producer Inco and equipment manufacturer Sandvik Tamrock launched the project five years ago; its goal was remote control, from the surface, of the machinery essential to hard-rock mining. Success means that for the first time workers would venture underground only to assemble the machinery and, occasionally, for maintenance work. Uninhabited tunnels would be smaller, and miners wouldn't have to hike a kilometer every morning just to reach equipment—advances that would mean higher productivity.**

The machines—outfitted with cameras and radio transmitters—are separated from the surface by hundreds of meters of rock, so they can use an unlimited range of radio frequencies without jamming surface transmissions. Partially unshielded coaxial cables fed into the mine serve as antennas, relaying real-time visual data to operators aboveground, who can control as many as three machines simultaneously with joysticks and foot pedals.

The project's first successes were a ceiling drill and a front-end loader; the remaining machines, including a truck for hauling ore, will roll out over the next five years. —Larry Hardesty

_TR_ recently described a study that predicted fuel-cell cars wouldn't be the cleanest running vehicles in 2020 _("Fuel Cells: A Lot of Hot Air?," TR March 2001)_. Many readers requested the study, "On the Road in 2020." It's at web.mit.edu/energylab/www, or you can send a $20 check payable to MIT Energy Laboratory to Karen Luxton, MIT Energy Laboratory, Room E40-391, 77 Massachusetts Ave., Cambridge, MA 02139.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UPSTREAM

SPOTLIGHT ON A HOT TECHNOLOGY TO WATCH

Protein Chips

New microarrays show how proteins interact

THE COMPLETION OF THE Human Genome Project last year marked a milestone in medicine. The detailed mapping of the entire set of human genes was a decade-long project worked on by some of the best minds in biology. But in many ways it was only the beginning of the real medical challenge: understanding the million or so proteins that are the molecular workhorses of the human body. Genes are really just the programming code that tells cells how to synthesize proteins; almost all the biological action occurs among these large, complex molecules.

When proteins misbehave they can destroy our health in myriad ways, from the amyloid proteins that gum up the brains of Alzheimer's patients to the proteins that cause runaway cancer-cell growth. Battling disease more effectively means getting a better grip on how proteins work and interact—and fail. The most important emerging tools in reading the vast protein library are microarrays, small chips containing thousands of protein samples that can be analyzed quickly and cheaply. "This is where people will get answers about how disease develops, how drugs work, and how to find new drugs," says Peter Wagner, chief technical officer of Zyomyx, a Hayward, CA-based protein-chip startup.

Zyomyx has nearly a dozen competitors, including Large Scale Proteomics, Ciphergen Biosystems, Packard BioScience and Phylos. The industry's first products are expected on the market in a year, and while technologies vary, the new biochips are generally two-dimensional grids of proteins or protein fragments attached to a solid support.

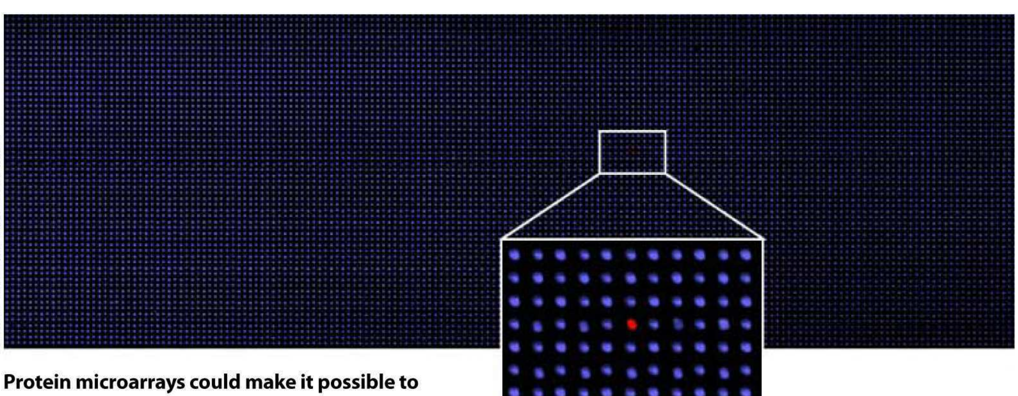
When the protein microarray is exposed to biochemicals or solutions of other proteins, some of those molecules will stick and some will wash off; the ones that stick can be identified by various markers, such as fluorescent tags. Molecules that adhere strongly to specific proteins are valuable leads in the search for new drugs, because that binding ability is what makes pharmaceuticals effective. And for diagnostics, measuring abnormally high amounts of telltale proteins in a blood sample using these biochips could be a fast method for early detection of heart attacks and cancer.

The idea of microchips is nothing new in biology. The manufacture of DNA chips has been one of the hottest areas of biotech since the early 1990s, when innovative researchers took the robotics and lithographic-patterning technology used in making silicon microelectronics and applied them to DNA analysis. They were able to attach thousands of pieces of genetic material to glass slides or plastic wafers and use these "chips" to identify DNA in a sample of interest. These DNA chips are now widely used in medical research.

But making a protein chip is far more vexing. While DNA is pretty sturdy, proteins are shrinking violets. Proteins are exquisitely folded strings of subunits called amino acids, and a lot of what proteins do depends on the precise three-dimensional pattern that the string folds into. Outside of a narrow range of environmental conditions, proteins will "denature"—the amino-acid chain will lose its three-dimensional structure, collapsing like a pile of overcooked spaghetti. In making microarrays, researchers have to keep the proteins in a watery solution at just the right temperature the whole time.

Despite these challenges, the future of protein biochips is unfolding rapidly. "There is a clear understanding everywhere in the [biotech] industry now that you've got to focus on proteins," says Zyomyx's Wagner. According to a recent report by BioInsights, a biotech consulting firm in Redwood City, CA, sales of protein biochips will likely rocket to half a billion dollars in 2006.

And the eventual impact of the technology may be felt far outside the biological research community. "Useful protein chips for diagnostics should be available in a couple of years," says N. Leigh Anderson, CEO of Large Scale Proteomics. "It won't take as long as some people think." That might be an optimistic prognosis, but if he's right, packages of small protein chips may soon be just as ubiquitous as tongue depressors or rubber gloves in your doctor's office. **—David Voss**



Protein microarrays could make it possible to quickly and cheaply test thousands of protein samples. To demonstrate that they could pick a protein of interest out of a vast array, researchers at Harvard University's Center for Genomic Research prepared a 2.5-centimeter-by-7.5-centimeter slide that held 10,799 samples of one protein and a single dot of another protein. They then exposed the array to two compounds (one fluorescently tagged blue, the other red); the blue-labeled compound selectively attached to the first protein and the red-labeled compound to the second protein. A close-up of the slide shows how the technique can clearly detect the single protein sample (shown in red) out of the thousands of other samples.

TR100 NOMINATION FORM

Technology Review is seeking nominations for its 2002 edition of the "TR100"—one hundred young men and women who are making significant contributions to emerging technologies that will have a profound impact on our world. Nominees must be under age 35 on January 1, 2002, and their work should exemplify the spirit of innovation. *Technology Review* will profile each finalist in a special January 2002 issue, and recognize them at a gala dinner and awards celebration. Thank you for your nomination!

NOMINEE* ______________________

INSTITUTION ______________________

ADDRESS ______________________

PHONE* ______________________

E-MAIL* ______________________

AGE* ______________________

TECHNICAL AREA OF NOMINEE'S WORK:

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BRIEFLY DESCRIBE THE NOMINEE'S WORK SO FAR:

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WHY DO YOU THINK THIS PERSON MIGHT BE ONE OF THE TOP 100 YOUNG INNOVATORS?

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PLEASE PROVIDE CONTACT INFO FOR OTHER REFERENCES (UP TO 3) FOR YOUR NOMINEE:

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NOMINATOR* ______________________

INSTITUTION ______________________

ADDRESS ______________________

PHONE* ______________________

E-MAIL* ______________________

RELATIONSHIP TO NOMINEE: ______________________

*required info.

Please fax form to 617-258-8778 c/o Celia Wolfson or mail to her at Technology Review, 201 Vassar St., Cambridge, MA 02139.
Or use our online form at www.technologyreview.com.

PB&J Patent Punch-up

Forget the hubbub over Napster, or even that inane "one-click" lawsuit between Amazon.com and Barnes & Noble. We need to talk about the IP food fight over U.S. Patent 6,004,596.

Hold on to your lunchboxes, *Technology Review* readers. This legal squabble pits J. M. Smucker, beloved maker of jam, against tiny, Gaylord, MI-based Albie's Foods. For reasons that elude me, Smucker's lawyers decided to try to enforce the firm's exclusive rights to—I'm not making this up—its patented version of a peanut butter and jelly sandwich.

Owning the PB&J sandwich? Talk about an affront to mom and apple pie!

Now, it's the reasoning of the Smucker legal eagles that I really want to address. But I know you levelheaded *Technology Review* readers will find the notion of a patented PB&J pretty, well, hard to swallow. So before we go further, I invite you to look it up for yourself. (Go to www.uspto.gov/patft and enter the aforementioned patent number.) Then you too can marvel at this U.S. patent, granted in December 1999. You can experience firsthand its claim to a "first bread layer having a first perimeter surface coplanar to a contact surface" and its careful legalistic delineation "wherein said first filling" is "comprised of peanut butter" and a "second filling is comprised of a jelly."

To uphold my commitment to journalistic accuracy, I must acknowledge that Smucker (through its Ohio subsidiary Menusaver) has not patented any old PB&J, but a breathtakingly novel version called a "sealed crustless sandwich." Smucker markets the peanut butter and jelly sandwiches as "Uncrustables," proclaiming them to be "the perfect 'grab-and-go' sandwich for families on the move."

Furthermore, I must note that I have not yet had the opportunity to personally sample an "Uncrustable." Still, at the risk of spurring further lawsuits, I cannot help but notice from the picture on the box that they look suspiciously similar to plump, untoasted Kellogg's Pop-Tarts! But I digress.

It is the legal reasoning that interests me, and it begins with Smucker's justification for its claim of exclusivity. As Smucker's lawyers explain in the patent, "There is currently no method or device for baking bread without having an outer crust. Hence there is a need"—people, there is a need!— "for a convenient sandwich which does not have an outer crust and which is not prone to waste of the edible outer crust portions."

Owning the peanut butter and jelly sandwich? Overreaching IP legal teams kick the firms they supposedly represent.

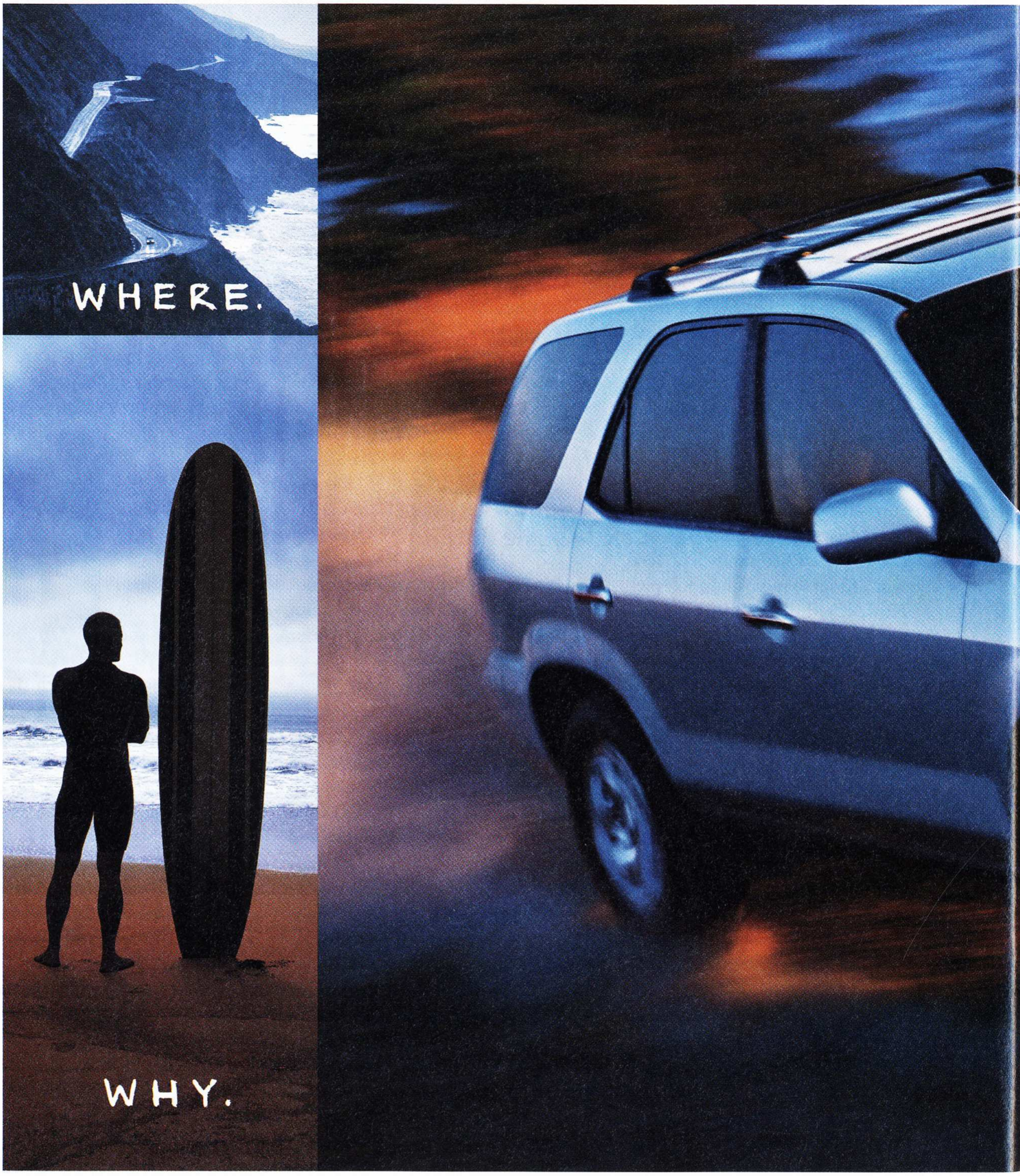
The truth is, leaving aside, if you can, the colossal idiocy of this patent, we are confronted with the monumentally misguided judgment of the Smucker lawyers in actually trying to enforce it when Albie's started making their own crustless peanut butter and jelly sandwich—the E.Z. Jammer. And—all kidding aside—the Smucker debacle epitomizes the biggest problem with intellectual property as it is practiced today: it's so often dramatically overreaching.

Overreaching copyright claims, overreaching patents, overreaching trademarks, overreaching litigation, and overzealous lawyers who ought to be ashamed. In equestrian circles, they say a horse overreaches when its hind legs extend so far forward they kick the forelegs. It's a fitting image. In today's wild world of intellectual property we find pervasive evidence of overreaching legal teams kicking the firms they supposedly represent. Do the Smucker folks really think they can win anything worthwhile by achieving crustless PB&J supremacy over a small rival? Could it possibly be worth the bad press and ever-rising legal fees as the case wends through the courts?

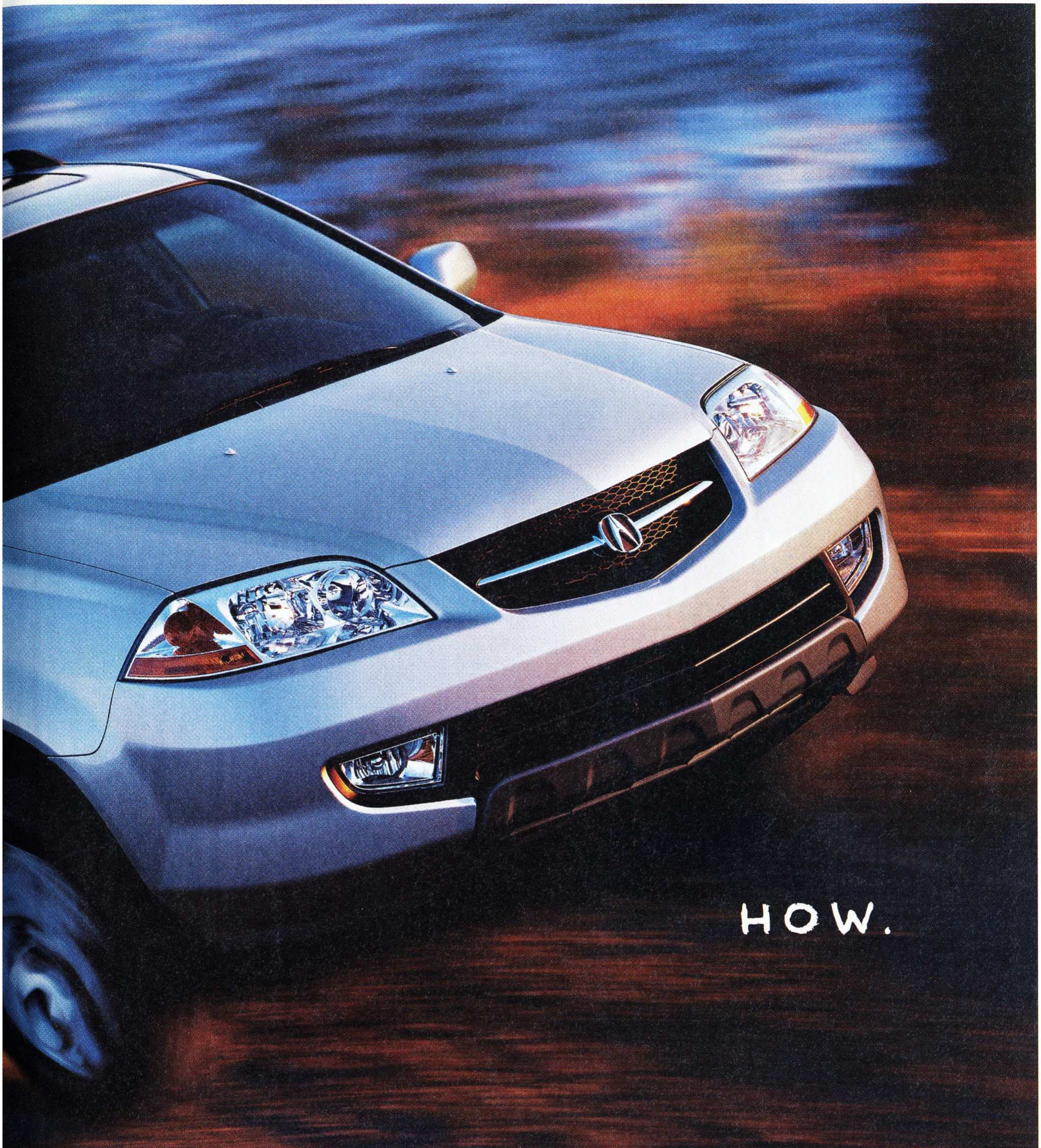
In homage to the Earl of Sandwich, who I'm sure is turning in his grave, I've singled out the Smucker case. But everybody I talk to seems to have their favorite examples—and I welcome further nominations. To start things rolling, though, here are a few others worth an honorable mention:

- The legal acumen of British Telecom in dusting off a dubious 1989 patent (one of those "Rembrandts in the attic") and starting to sue others claiming it has exclusive rights to the hyperlink that makes the Web possible. (And you thought Al Gore invented the Internet!)
- Ralph Lauren's victory in appeals court last year, when his lawyers forced a magazine begun in 1975 as the official publication of the U.S. Polo Association to change its name. What gall: they had called it *Polo.* Didn't they know that is a line of clothing and accessories?
- Mattel's efforts to uphold the good and profitable Barbie name. In only the most recent in a long list of similar actions, Mattel dragged Utah artist Tom Forsythe to court for trying to exhibit a photo series called "Food Chain Barbie" that depicted the doll in various culinary poses, including wrapped in a tortilla, smothered with enchilada sauce.

This last case is an especially rich example of IP overreach. I mean, I don't know if it's art, but haven't Mattel's lawyers heard of the First Amendment? I'm just glad Forsythe didn't seal Barbie in a crustless PB&J, or he'd probably have J. M. Smucker's lawyers after him too. ◊



Introducing Acura MDX. *It wasn't about finding shortcuts. We designed the 240-hp MDX with one mission. To deliver more. More power, performance and flexibility than just about any other luxury SUV in its class. So, if you're climbing dirt roads along Half Moon Bay, you'll appreciate a leather-appointed interior, split fold-down*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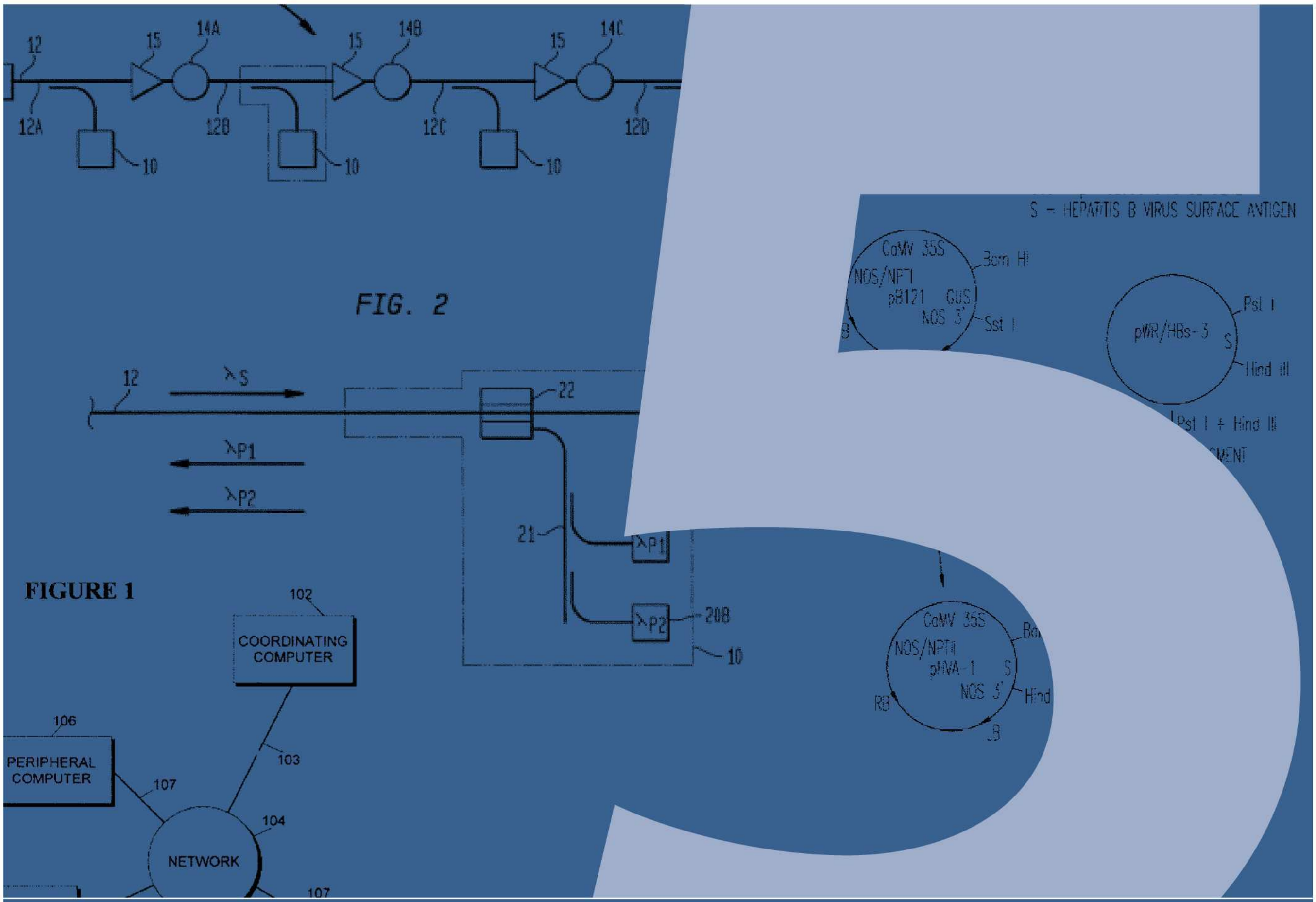


PATENTS TO WATCH

A handful of hot new patents that may change the way business and technology get done.
Illustrations by Ron Carboni and Betsy Hayes

Growing human organs to ease the deadly shortages facing patients desperate for transplants. Deploying organic molecules to store a million times more data than silicon can. Harnessing the unused processing power on your desktop to attack gigantic computational problems, from genetic analysis to spotting hidden customer trends. Massively expanding the data capacity of optical networks to turbocharge the information superhighway. Modifying plants to grow cheap, lifesaving vaccines.

If these sound like far-out, grandly ambitious ideas—well, they are. But they may touch your life sooner than you think, since all of these conceptions are close enough to reality to have received patents in the year 2000. And, as a result of this combination of sweeping vision and nitty-gritty reality, they've been selected by the editors of *Technology Review* for "5 Patents to Watch," a special section highlighting some of last year's most intriguing and potentially world-changing patents.

Of course, we cannot say with certainty which of the 182,223 patents issued last year by the U.S. Patent and Trademark Office will prove to be the most significant in the long run. And the insiders in this game know that. When *Technology Review* asked MIT Technology Licensing Office director Lita Nelsen to help pinpoint last year's most significant patents, she just chuckled: "You want to borrow my dart board?"

That didn't stop us, though. And we didn't use her dart board, either. Instead, we established some solid criteria that made the task manageable. The patents we chose had to be at the cutting edges of important fields. They had to go beyond scientific advances to represent technological trends with the potential to transform existing businesses or create new industries.

Each of the final five is at the center of a current technology hotbed. Many others are working in each of these fields. Therefore, we decided to put our selections in context by showcasing other notable predecessor, rival or complementary patents. These appear in tables accompanying the patents' descriptions.

Joining the section on 5 Patents to Watch, you'll find our second annual Patent Scorecard, which tracks the U.S. patenting activity of 150 leading firms in eight key high-tech sectors *(see "Companies Squeeze the Patent Pipeline,"* TR *March/April 2000)*. By reading the five patent profiles and then reading the scorecard, you'll get both an in-depth look at some technology hot spots and a broad overview of patenting trends by industry. Let us know how you like it. **—The Editors**

COLLECTIVE COMPUTING

The future of big computing may lie in distributing the work.

TITLE	Task distribution processing system and the method for subscribing computers to perform computing tasks during idle time
NUMBER	US6112225
APPLICANT	IBM
ISSUED	August 2000

For years, researchers have worked to tap the powers of many remote computers to accomplish large computational tasks, from cracking encryption algorithms to gene sequence analysis. While this "distributed computing" isn't new, the proliferation of home and office computing, along with the spread of the Internet, is heightening interest in developing technologies to exploit today's multitude of machines. One example is SETI@home, a free program from the University of California, Berkeley. When a user's screen saver kicks on, the program signals the SETI@home host computer over the Internet that the local computer is available to join the Search for Extraterrestrial Intelligence. The PC is sent a slice of cosmic radio-frequency data, which it analyzes for anomalies indicative of alien communication (none found so far, sorry).

But while some experts call distributed computing a generic approach to which nobody has a proprietary claim, U.S. patent examiners think otherwise. Last year IBM won an apparently broad patent on a way to broker large computing tasks. Rather than locking machines into one SETI-like job, the method can handle many tasks. And while Big Blue is guarded about how its patent relates to other distributed-computing work, one insider says it could bring distributed computing into general use. "Distributed computing is part of the way we're looking at how future computing networks are going to operate," the executive says. "That affects our software strategy, hardware, server [and] service [businesses]."

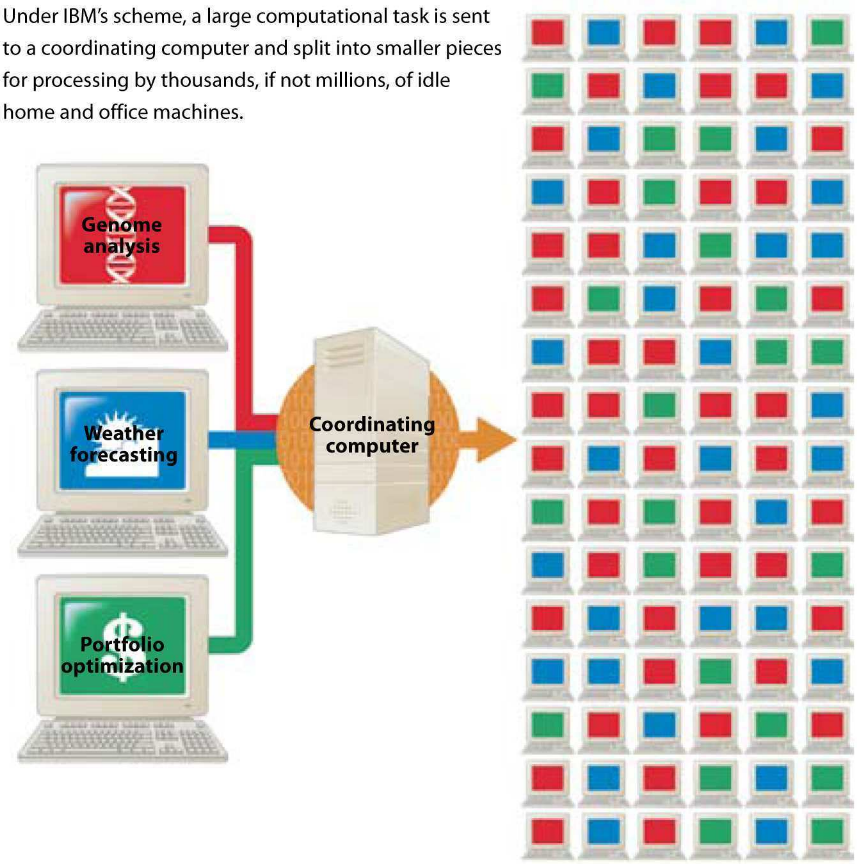
The patent, filed in March 1998, before SETI@home became available, describes how a coordinating computer splits up a large task. Peripheral computers "subscribe" to this central computer and get a special screen saver. When the screen saver is activated, the subscribing computer alerts the central machine and receives its job. It works on this task whenever it's idle and sends back the results. "We saw there was a huge amount of machines sitting around idle at corporations that were connected to the Internet but were not used for any tasks," says co-inventor Reiner Kraft of IBM's Almaden Research Center in San Jose, CA. "We thought of expediting this kind of work, and making it easy for people to use."

Big Blue says this approach has applications for high-end computing workloads including genome analysis, crunching financial data, weather forecasting and anything graphics-intensive—especially in small and medium-sized companies that can't afford a dedicated mainframe. IBM even envisions spot markets in computation, in which a broker would take on big jobs and farm out the work to home or office machines whose owners receive a small payment—a few cents—in return for making their PCs available.

IBM's patent is not yet well known, so it's hard to get experts to comment on its likely impact. But the field is hot, with many corporate and university researchers developing other distributed-computing strategies. "Many things that actually occur in the Internet today really are distributed tasks," says Rick Rashid, senior vice president at Microsoft Research.

IBM agrees, and believes it has staked a key claim on the area. So even if your computer never finds alien life, it might identify a gene sequence that helps save lives here at home. And earn you some pocket change, to boot. —**David Talbot**

Under IBM's scheme, a large computational task is sent to a coordinating computer and split into smaller pieces for processing by thousands, if not millions, of idle home and office machines.



RON CARBONI

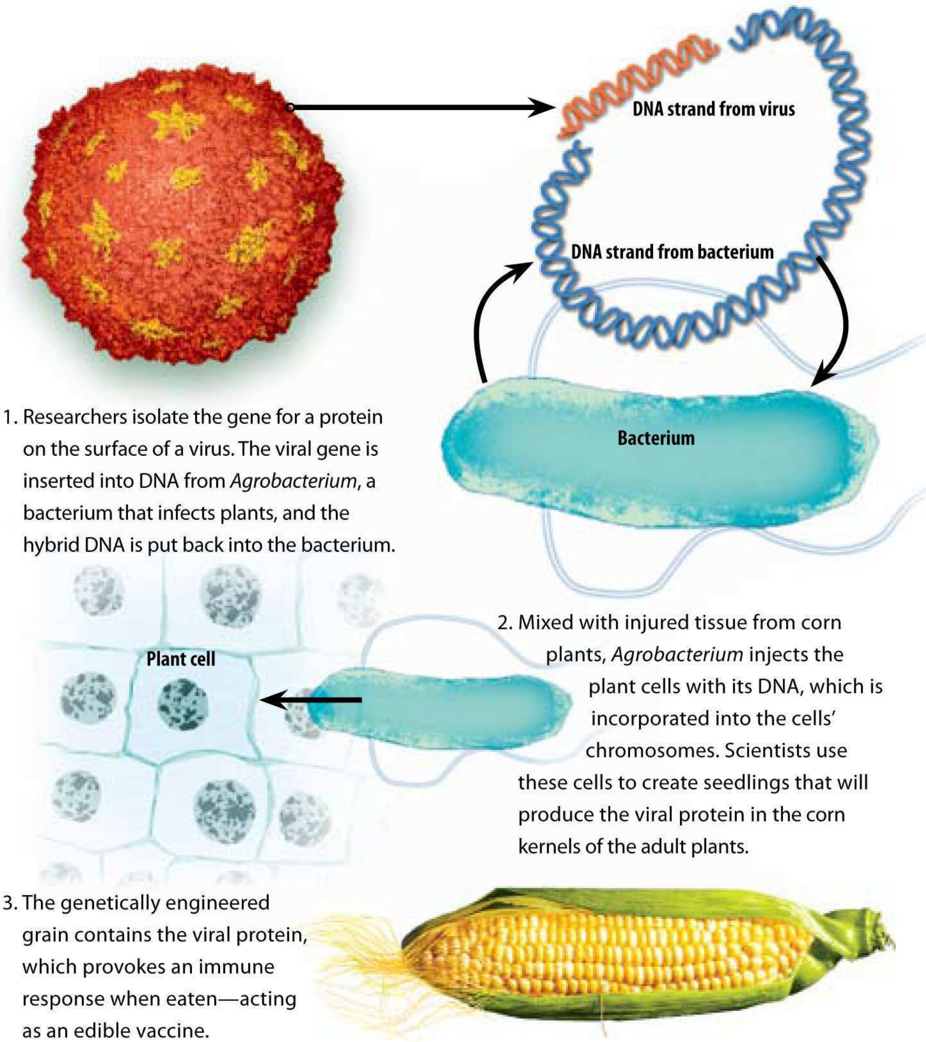
OTHER DISTRIBUTED-COMPUTING PATENTS	
US5978594 (November 1999) BMC Software	Managing computer resources in distributed-computing environment
US5740549 (April 1998) PointCast	Information distribution system using screen-saver method
US5655081 (August 1997) BMC Software	Distributed computing using intelligent-agent architecture

HEALTHY SNACKS

Vaccines you eat will make immunization less painful and more accessible worldwide.

NOS/NPT pB12 RB

Vaccines expressed in plants	TITLE
US6136320	NUMBER
ProdiGene	APPLICANT
October 2000	ISSUED



1. Researchers isolate the gene for a protein on the surface of a virus. The viral gene is inserted into DNA from *Agrobacterium*, a bacterium that infects plants, and the hybrid DNA is put back into the bacterium.

2. Mixed with injured tissue from corn plants, *Agrobacterium* injects the plant cells with its DNA, which is incorporated into the cells' chromosomes. Scientists use these cells to create seedlings that will produce the viral protein in the corn kernels of the adult plants.

3. The genetically engineered grain contains the viral protein, which provokes an immune response when eaten—acting as an edible vaccine.

BETSY HAYES

Taking the kids to the doctor can be a battle, especially when they need a shot. But soon children and adults alike could receive vaccines from corn puffs or a jar of baby food.

Edible vaccines grown in corn, bananas or tomatoes could not only make vaccination more convenient in wealthier countries but help global immunization efforts *(see "Making Needles Needless,"* TR *September/October 1998)*. Barriers to immunization in poor countries include the cost of vaccines and needles, lack of health-care workers and difficulty in refrigerating the doses. Hepatitis B vaccine, which costs 50 cents for each dose, remains out of reach for many of the world's poor; over 900,000 people die each year from hepatitis B. Producing the vaccine in plants could reduce the cost to less than a penny per dose. And simple food processing like drying and grinding could create nonperishable preparations.

ProdiGene, based in College Station, TX, is working to bring edible vaccines to the marketplace. ProdiGene creates its vaccines by genetically engineering corn to produce bacterial or viral proteins that elicit immune responses when eaten. Last year, the company received a patent covering any viral vaccine produced in any plant. ProdiGene has also filed patents on edible bacterial vaccines, says chief scientific officer John Howard. The company plans to test an *E. coli* vaccine in humans this year and hopes to do the same for a hepatitis B vaccine early next year.

Lead inventor on the patent is Charles Arntzen, a plant molecular biologist who originated the idea of plant-grown vaccines a decade ago at Texas A&M University. Arntzen, now at Arizona State University, is not affiliated with ProdiGene; the company bought rights to the technology from Texas A&M. Arntzen says the ProdiGene work is interesting, but points out there are other tacks. "Since there is a potential for at least a hundred different vaccines for different viruses, I would expect that there's not going to be any single technology approach. It's really going to be disease specific; it's going to be specific for the population that you're trying to immunize," Arntzen says.

Indeed, three separate patents covering edible vaccines issued in 1997 to Washington University in St. Louis are now licensed to Dow AgroSciences. But David Wheat, an analyst at the Boston-based Bowditch Group, says ProdiGene is in a good position. "ProdiGene is reputed to have made sure to have good, tight access to all of the intellectual property they need. They will be able to practice this technology without roadblocks from other companies," he says.

While a number of academic groups are developing edible vaccines for humans, ProdiGene is the only company pushing ahead with human clinical trials. "We believe that the opportunities are tremendous," says Howard. "We also know there's other people looking at it, and what we'd like to do is work with all those other people. We would like to see above all the technology go forward." —**Erika Jonietz**

OTHER EDIBLE VACCINE PATENTS	
US5958422 (September 1999) Axis Genetics	Using plant viruses to produce proteins and plants to deliver them
US5654184, US5679880, US5686079 (Fall 1997) Washington University	Plants genetically engineered to produce viral or bacterial proteins and using such plants as vaccines
US5670349 (September 1997) Virginia Tech Intellectual Properties	Tobacco plants genetically engineered to produce foreign proteins

BOOSTER SHOTS

New Raman amplifiers are key to building an all-optical Internet.

TITLE	Optical communication system using multiple-order Raman amplifiers
NUMBER	US6163636
APPLICANT	Lucent Technologies
ISSUED	December 2000

Light flashing through optical fibers forms the backbone of today's high-speed telecommunications networks. It's the technology that makes possible the Internet as we know it, and, in the not-too-distant future, it could make possible an "all-optical Internet" *(see "The Microphotonic Revolution,"* TR *July/August 2000)*. Relying totally on fiber optics to transmit data, an optical Internet will offer enough bandwidth to deliver far more compelling online entertainment, education and e-commerce; there will even be sufficient bandwidth to hold video conferences in which the slightest changes in facial expression—and perhaps even smell and touch—are immediately apparent.

One hang-up in transmitting light signals through fiber optics, however, is that the light tends to peter out over distance. Every 70 kilometers or so in an optical fiber, amplifiers are needed to boost the signals. These devices are expensive and can break down; if that happens, say, in the middle of an optical cable buried in the Pacific Ocean, it's a costly headache. What's more, as telecommunications companies look to push more and more data through fiber optics, by squeezing multiple wavelengths of light within a single fiber *(see "Wavelength Division Multiplexing,"* TR *March/April 1999)*, amplifiers are having a tough time keeping up with the complexity of the signals.

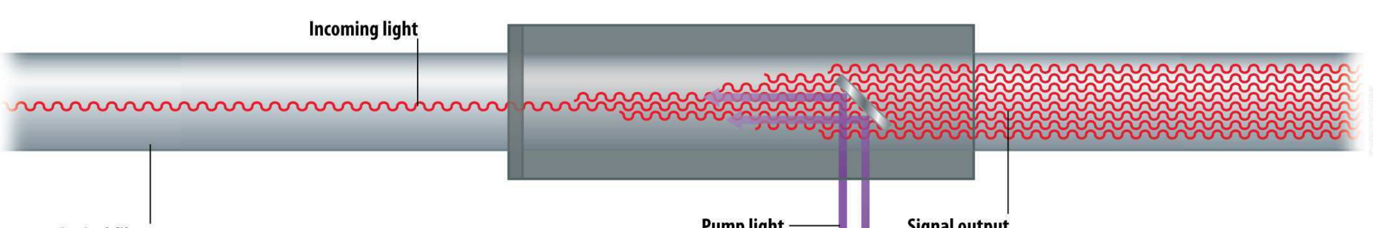
With that in mind, researchers at Lucent Technologies' Bell Labs have developed a new generation of optical amplifiers that take advantage of a well-known effect in laser physics called Raman scattering. Raman amplifiers are based on a rather improbable premise: to amplify a light beam, blast the medium through which it is traveling, using another beam coming from the opposite direction. (C. V. Raman won the 1930 Nobel Prize in physics for observing the general effect.) In the latest version of Raman amplification, Lucent has developed a device that uses multiple lasers to boost light signals in an optical fiber, allowing the signals to travel much farther before they need to be boosted again. In addition, this newest design should make it possible for amplifiers to keep up with the all-optical Internet that's on the horizon.

A 1999 patent issued to Lucent describes a new type of Raman amplifier that is "used in almost all the new ultralong-distance systems being developed," says coinventor Kenneth Walker. In last year's patent, Bell Labs researchers led by Walker and Andrew Stentz followed up with the invention of a "multiple-order" Raman amplifier that adds a second laser pump; the lasers work in tandem to extend the duration of light signals traveling through an optical fiber. The design is also capable of working with future optical transmission equipment that will transmit data over a greater portion of the optical spectrum to boost bandwidth even further. Both versions exploit an inherent advantage of Raman amplifiers: they disrupt the data carried by light much less than other methods of amplification do, thus eliminating costly equipment used to correct the signals.

The recent design improvements from Bell Labs and others are now catapulting the technology into the mainstream of telecommunications. According to Strategies Unlimited, an analyst firm in Mountain View, CA, Raman amplifiers could grow from a fraction of the $3.3 billion optical amplifier market at year's end 2000 to about half the total $7.3 billion market in 2004.

The all-optical Internet is still a few years away. But when it arrives, Lucent's latest version of Raman amplification may be one of its building blocks, bringing more bandwidth directly to your desktop and your handheld wireless device. —**Eric S. Brown**

OTHER RAMAN AMPLIFICATION PATENTS	
US5959750 (September 1999) Lucent Technologies	Raman amplification for dense wave-division multiplexing systems
US5673280 (September 1997) Lucent Technologies	Low-noise Raman amplifier (reduces noise interference)
US4616898 (October 1986) Polaroid	First commercially practical Raman amplifier



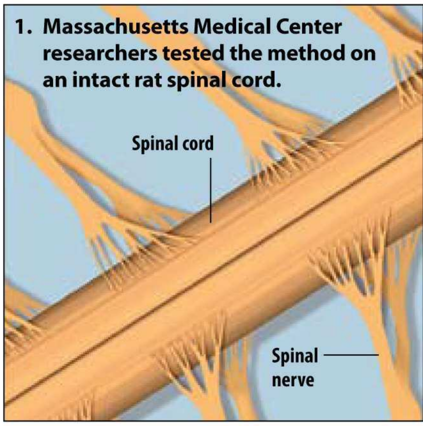
Intense pump light from a pair of lasers is used to excite vibrational modes in the silica molecules that form the optical fiber. The energy in the vibrational excitations amplifies the signal in a process called "stimulated Raman scattering." As they excite the molecules, the pump beams lose energy.

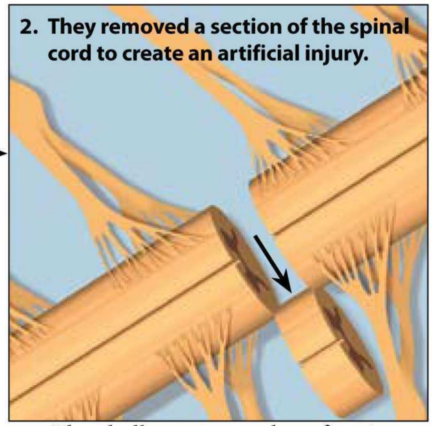
The amplified light continues through the optical fiber, with little distortion of the signal. The technique can be used to amplify a desired signal wavelength through careful selection of the appropriate pump wavelengths. In addition, it works over a broad range of wavelengths.

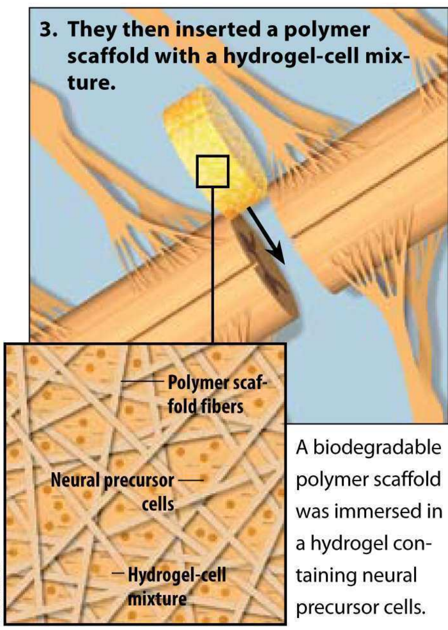
GROWTH INDUSTRY

Tissue engineering promises to repair and even replace damaged body parts.

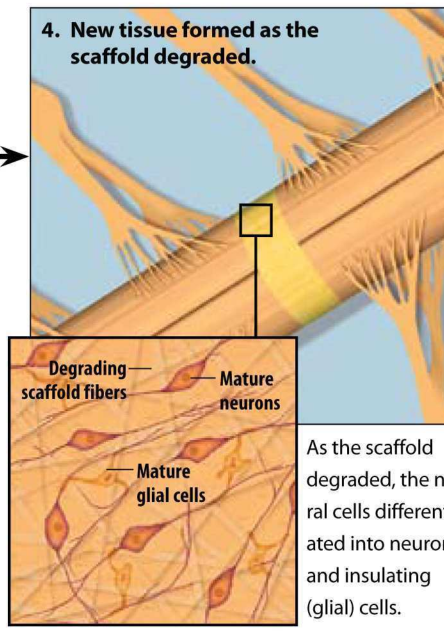
Guided development and support of hydrogel-cell compositions	**TITLE**
US6027744	**NUMBER**
University of Massachusetts Medical Center, Boston; The Children's Medical Center Corporation, Boston	**APPLICANTS**
February 2000	**ISSUED**







A biodegradable polymer scaffold was immersed in a hydrogel containing neural precursor cells.



As the scaffold degraded, the neural cells differentiated into neurons and insulating (glial) cells.

BETSY HAYES

Tissue engineering is the art of taking a sample of cells and "growing" them under the right conditions to form tissue—even whole organs. Skin, bone, and cartilage products based on the technology are already on the market, and engineered bladders and heart valves are showing promise in the lab *(see "The Human Body Shop," TR April 2001).*

The driving force behind tissue engineering is the shortage of human organs for transplantation. But that isn't the only factor. Transplants are expensive and technically difficult, and patients are bound to lifelong drug regimes to prevent their bodies from rejecting the organs. A patent based on the work of Jay and Charles Vacanti, siblings who are pioneers in the field, could begin to change all that.

The challenge researchers face is getting cells to grow into tissue with the same shape and properties as native tissue. One common method involves adding cells to a biodegradable polymer scaffold, which is then implanted in the body. The problem is that it's hard to keep the cells attached to the polymer. "You need to make sure they're evenly distributed throughout the scaffold, or else they fall and clump together," says Linda Griffith, a tissue engineer at MIT. Another approach is to mix cells in a hydrogel, a Jell-O-like polymer, to keep them in place; the hydrogel, however, can't hold a three-dimensional shape.

The Vacantis decided to combine these two techniques. The first part of their patented method involves taking a polymer scaffold and molding it into the shape of a tissue, like a blood vessel or a piece of liver; the scaffold is then immersed in a liquid hydrogel containing tissue-precursor cells. When implanted in the body, the hydrogel hardens, keeping the cells in place. "It's like reinforced concrete," says Jay Vacanti, based at Massachusetts General Hospital. "And the new tissue looks just like the one it was replacing."

Charles Vacanti's lab at the University of Massachusetts Medical Center tested the system on rats by removing a section of the spinal cord to simulate a spinal cord injury. They then implanted a polymer scaffold that had been seeded with a hydrogel mixture containing neural precursor cells. After a couple of months, not only did new tissue form, but the precursor cells developed into both regular nerve cells and the insulating glial cells that facilitate transmission of nerve impulses. As a result, most of the animals regained the ability to move their lower limbs.

In the future, the technique could also be used to repair birth defects or replace lost joint cartilage in people with arthritis. And, further down the road, the Vacantis hope to use the technology for growing whole organs. —**Alexandra Stikeman**

OTHER TISSUE ENGINEERING PATENTS

US5759830 (June 1998) Children's Medical Center, Boston/MIT	Three-dimensional scaffolding made from biodegradable plastic
US5624840 (April 1997) Advanced Tissue Sciences	Using a three-dimensional biocompatible structure to build tissue from liver cells
US5041138 (August 1991) Children's Hospital, Boston/MIT	Cartilaginous structure made using a synthetic polymer matrix

MOLECULAR MEMORY

Replacing silicon with organic molecules could mean tiny supercomputers.

TITLE	Molecular wire crossbar memory
NUMBER	US6128214
APPLICANT	Hewlett-Packard
ISSUED	October 2000

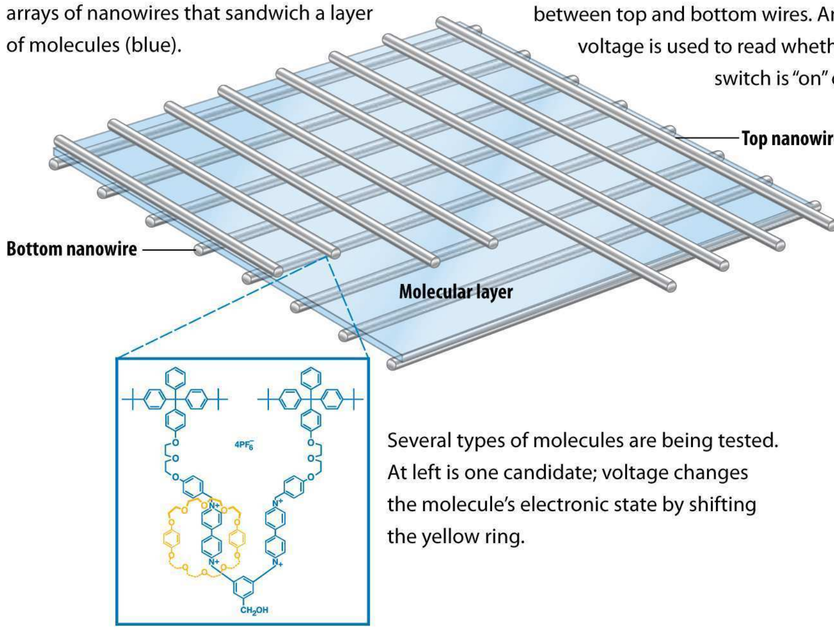
The brains of a computer is the semiconductor chip. Much of the progress over the last 35 years in making computers faster, smaller and cheaper has been a numbers game, squeezing ever more transistors and other electronic devices onto this postage-stamp-sized piece of silicon. Today's PCs pack tens of millions of transistors onto a chip, each transistor as small as a few hundred nanometers (billionths of a meter). But continuing this miniaturization will not be easy—or cheap. Some experts predict that by 2010 it will cost from $30 to $50 billion to build a manufacturing facility to fabricate even smaller chips. Then again, a number of physicists contend the price tag won't matter, because silicon-based devices are fast reaching their fundamental physical size limits.

So what if, instead of carving transistors and other microelectronic devices out of chunks of silicon, you used organic molecules? Even large molecules are only a few nanometers in size; an integrated circuit using molecules could contain trillions of electronic devices—making possible tiny supercomputers or memories with a million times the storage density of today's semiconductor chips *(see "Molecular Computing,"* TR *May/June 2000)*. It may sound like science fiction, but several leading industrial and academic labs are already fashioning rudimentary devices based on "molecular electronics," and several startups have been formed to commercialize the technology.

OTHER NANOELECTRONIC PATENTS	
US5783840 (July 1998) Texas Instruments	Method for making quantum-dot logic device
US5589692 (December 1996) Yale University	Sub-nanoscale electronic systems and devices
US4987312 (January 1991) IBM	Process for repositioning atoms using a scanning tunneling microscope

The memory device is made of crossbar arrays of nanowires that sandwich a layer of molecules (blue).

A voltage changes the electronic state of the molecules, and hence the resistance between top and bottom wires. Another voltage is used to read whether the switch is "on" or "off."



Several types of molecules are being tested. At left is one candidate; voltage changes the molecule's electronic state by shifting the yellow ring.

RON CARBONI

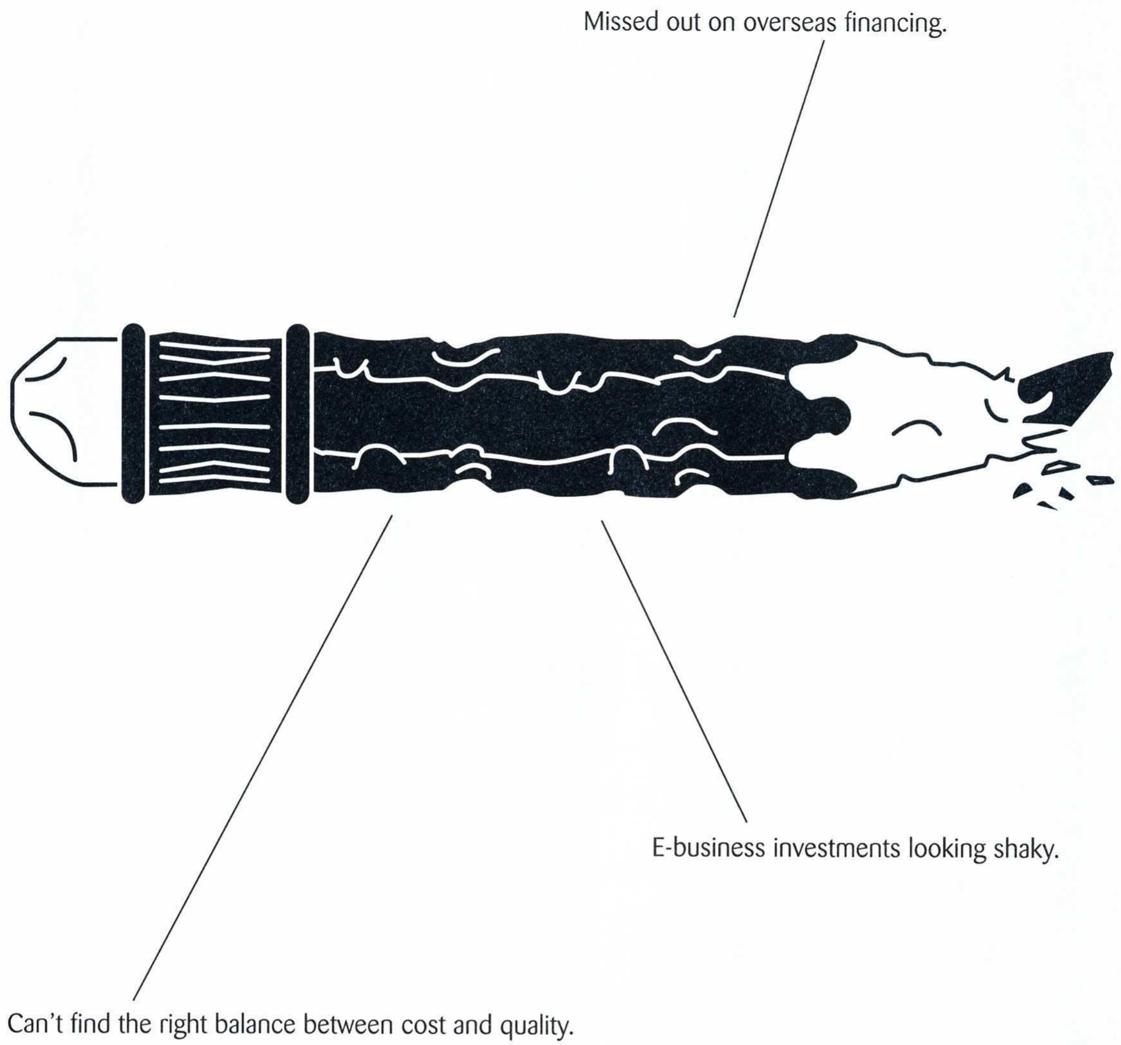
Nowhere have the advances been more impressive—or the ambitions greater—than at Hewlett-Packard Laboratories in Palo Alto, CA *(see "Computing after Silicon,"* TR *September/October 1999)*. Late last year, HP's research group, led by Philip Kuekes, R. Stanley Williams and University of California, Los Angeles chemist James Heath, received an initial patent on a molecular memory device; a series of related patents covering everything from molecular logic to how to chemically assemble these devices is pending.

"We're trying to reinvent the integrated circuit, with all its functions," says Kuekes, a computer architect. The memory patent, he says, "is fundamental to our strategy. It's one of the legs for us to stand on." Besides being critical to one day building a molecular computer, he says, molecular-based memory incorporated into more conventional silicon microelectronics could be the first commercial application of molecular electronics. Kuekes predicts the group will have a prototype memory device within a year.

The HP patent describes a memory device built from crossbar arrays of nanowires sandwiching molecules that act as on/off switches. In writing a bit, one voltage decreases the electrical resistance through the molecules, turning the switch "on"; at another voltage, the molecules are turned "off." One advantage of the technology, says Kuekes, is that hardware engineers will be familiar with the design; except for the remarkable fact that it utilizes organic molecules, not silicon or magnetic particles, the technology resembles electronic memories used in PCs. "We want to make sure that what's here is truly useful to build computer systems and is useful in ways that computer designers can understand," says Kuekes.

The HP patent is one of the first to issue that covers a molecular electronic device. However, several groups have patented related nanoelectronics technologies. And a number of other patents on devices that take advantage of molecular electronics are pending at the U.S. patent office.

While it's too early to predict the winner of this race to build and commercialize molecular electronics, those following the field say these initial patents could be critical. "They will be very valuable in all the R&D that builds off them," says James J. Marek Jr., chief executive officer of California Molecular Electronics, a startup that has licensed the rights to several technologies. "These are the building blocks." —**David Rotman**



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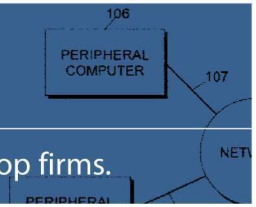

We ranked companies in key industries according to the quality and quantity of their patents. Here are 150 of the world's top firms.

	COMPANY	COUNTRY	TECHNOLOGICAL STRENGTH/RANK 2000	TECHNOLOGICAL STRENGTH/RANK 1995-99*	NUMBER OF PATENTS 2000	NUMBER OF PATENTS 1995-99*	CURRENT IMPACT INDEX 2000	CURRENT IMPACT INDEX 1995-99*	SCIENCE LINKAGE 2000	SCIENCE LINKAGE 1995-99*	TECHNOLOGY CYCLE TIME 2000	TECHNOLOGY CYCLE TIME 1995-99*
AEROSPACE	Lockheed Martin	U.S.	313/1	282/1	329	307	0.95	0.92	2.70	1.82	8.5	8.5
	United Technologies	U.S.	207/2	221/2	345	335	0.60	0.66	0.33	0.42	10.8	9.8
	Boeing	U.S.	153/3	187/3	232	223	0.66	0.84	0.54	0.78	11.4	13.0
	Rockwell International	U.S.	114/4	176/4	112	175	1.02	1.01	0.34	0.53	7.1	7.6
	Northrop Grumman	U.S.	96/5	113/5	132	145	0.73	0.78	0.37	0.63	9.3	8.9
	Thomson-CSF	France	74/6	83/6	97	113	0.76	0.73	0.58	0.69	8.8	8.1
	EADS	Netherlands	66/7	75/7	126	132	0.52	0.57	0.27	0.35	13.4	10.8
	Textron	U.S.	51/8	73/8	61	77	0.83	0.95	0.05	0.27	13.3	10.4
	Sequa	U.S.	40/9	16/11	29	16	1.39	1.01	0.07	0.38	10.3	13.5
	SNECMA	France	27/10	31/9	63	68	0.43	0.45	0.37	0.24	11.1	11.9
	General Dynamics	U.S.	22/11	12/12	28	14	0.80	0.81	0.04	6.28	12.4	10.8
	GKN	U.K.	19/12	23/10	28	37	0.68	0.62	0.04	0.24	12.1	9.4
	Alliant Techsystems	U.S.	13/13	6/13	13	10	0.98	0.63	0.92	1.33	13.3	10.6
AUTOMOTIVE	DaimlerChrysler	Germany	736/1	344/8	722	400	1.02	0.86	0.12	0.26	9.2	8.6
	TRW	U.S.	575/2	412/5	483	324	1.19	1.27	0.60	0.54	7.4	7.8
	Bosch	Germany	536/3	395/7	630	429	0.85	0.92	0.11	0.21	7.7	7.2
	Denso	Japan	529/4	444/2	468	373	1.13	1.19	0.18	0.30	6.7	6.9
	Honda	Japan	491/5	424/4	501	372	0.98	1.14	0.09	0.17	7.7	6.6
	Toyota Motor	Japan	472/6	405/6	414	324	1.14	1.25	0.39	0.36	6.2	6.2
	General Motors	U.S.	467/7	482/1	458	447	1.02	1.08	0.74	0.51	7.2	7.5
	Ford Motor	U.S.	307/8	434/3	370	398	0.83	1.09	0.50	0.32	8.4	8.3
	Nissan Motor	Japan	301/9	179/11	276	166	1.09	1.08	0.05	0.16	6.1	6.2
	Yazaki	Japan	264/10	240/9	311	224	0.85	1.07	0.02	0.02	6.3	6.7
	Eaton	U.S.	253/11	214/10	232	218	1.09	0.98	0.17	0.33	9.3	8.9
	Yamaha	Japan	203/12	117/14	190	151	1.07	0.78	0.03	0.02	7.3	8.6
	Aisin Seiki	Japan	200/13	165/13	167	155	1.20	1.06	0.54	0.51	6.0	6.8
	Lear	U.S.	169/14	105/16	155	85	1.09	1.23	0.52	0.90	9.2	9.9
	Delphi Automotive Systems	U.S.	169/15	108/15	155	101	1.09	1.07	0.19	0.25	5.9	6.6
	ITT	U.S.	167/16	167/12	185	173	0.90	0.97	0.08	0.25	8.9	7.8
	Fiat	Italy	163/17	62/17	160	99	1.02	0.63	0.17	0.20	10.8	10.8
	Breed Technologies	U.S.	114/18	42/18	65	25	1.75	1.68	0.03	0.04	5.9	6.3

BIOTECH/PHARMACEUTICALS	GlaxoSmithKline	U.K.	269/1	150/9	374	208	0.72	0.72	6.31	6.60	8.4	8.6
	Pharmacia	U.S.	178/2	222/3	349	332	0.51	0.67	16.64	10.10	10.4	9.6
	Isis Pharmaceuticals	U.S.	175/3	61/16	115	40	1.52	1.54	27.02	36.74	5.9	6.7
	Merck	U.S.	170/4	190/4	265	226	0.64	0.84	10.23	9.84	6.5	6.4
	Pfizer	U.S.	168/5	157/7	259	199	0.65	0.79	5.76	5.81	9.4	9.3
	Aventis	France	154/6	345/1	375	733	0.41	0.47	7.34	3.85	10.2	9.8
	Schering	Germany	147/7	68/15	112	78	1.31	0.87	6.10	5.52	8.2	8.7
	Roche	Switzerland	139/8	223/2	263	282	0.53	0.79	17.60	16.12	8.6	8.5
	Eli Lilly	U.S.	125/9	168/6	174	205	0.72	0.82	7.51	9.43	8.5	8.7
	AstraZeneca	U.K.	94/10	105/12	204	170	0.46	0.62	7.11	5.52	9.4	8.5
	Novartis	Switzerland	93/11	180/5	186	310	0.50	0.58	11.45	6.01	8.8	9.6
	Abbott Laboratories	U.S.	88/12	155/8	133	166	0.66	0.93	6.83	5.01	9.2	9.4
	Novo Nordisk	Denmark	75/13	84/13	183	132	0.41	0.64	3.92	6.79	7.8	8.2
	Affymetrix	U.S.	70/14	13/23	27	7	2.60	1.94	17.15	12.06	8.1	6.6
	Bristol-Myers Squibb	U.S.	63/15	123/11	117	160	0.54	0.77	10.38	9.25	9.8	8.6
	BioNumerik Pharmaceuticals	U.S.	53/16	5/24	23	5	2.32	0.99	23.70	18.23	3.0	9.3
	Alliance Pharmaceutical	U.S.	52/17	50/20	15	18	3.44	2.83	10.67	11.51	8.2	6.9
	General Hospital	U.S.	48/18	52/19	64	54	0.75	0.96	30.09	35.88	7.3	8.2
	Takeda Chemical	Japan	43/19	57/17	86	97	0.50	0.59	11.47	3.23	8.2	9.1
	Xoma	U.S.	42/20	27/22	16	14	2.61	1.88	28.75	45.11	5.3	5.5
	American Home Products	U.S.	41/21	136/10	98	115	0.42	1.18	13.58	9.84	8.1	7.0
	Schering-Plough	U.S.	40/22	54/18	63	78	0.64	0.69	15.70	10.28	7.0	10.0
	Incyte Genomics	U.S.	37/23	71/14	149	77	0.25	0.92	9.42	10.29	3.9	4.9
	Alza	U.S.	37/23	42/21	41	40	0.90	1.06	4.44	2.95	10.3	10.8
CHEMICALS	Procter & Gamble	U.S.	584/1	773/1	475	411	1.23	1.88	1.53	1.81	10.8	10.3
	3M	U.S.	558/2	703/2	494	541	1.13	1.30	2.14	2.34	10.6	10.6
	DuPont	U.S.	318/3	402/3	539	496	0.59	0.81	8.01	4.52	9.6	9.6
	BASF	Germany	283/4	317/4	725	598	0.39	0.53	1.58	1.93	10.1	10.3
	Bayer	Germany	182/5	251/5	467	523	0.39	0.48	4.07	2.04	10.3	9.4
	Bridgestone	Japan	166/6	98/12	187	132	0.89	0.74	0.53	1.25	10.7	10.6
	Dow Chemical	U.S.	158/7	181/7	184	230	0.86	0.79	6.47	4.39	10.8	9.8
	Cabot	U.S.	140/8	33/18	50	19	2.79	1.74	3.34	5.67	11.9	10.2
	Shin-Etsu Chemical	Japan	133/9	128/10	199	190	0.67	0.67	0.62	0.36	6.9	7.3
	Agfa	Germany	131/10	130/8	222	186	0.59	0.70	0.07	0.13	7.2	7.4
	E.ON	Germany	124/11	120/11	247	218	0.50	0.55	0.88	0.78	8.7	9.0
	Ciba Specialty Chemicals	U.S.	116/12	67/17	176	84	0.66	0.79	1.15	1.00	10.4	10.6
	L'Air Liquide	France	110/13	74/15	126	88	0.87	0.84	0.68	0.85	9.0	9.6
	Rohm and Haas	U.S.	103/14	236/6	136	205	0.76	1.15	1.51	0.67	9.1	7.6
	Air Products & Chemicals	U.S.	100/15	79/14	108	80	0.93	0.98	2.01	1.29	10.1	9.2
	Dow Corning	U.S.	92/16	130/8	143	167	0.64	0.78	0.95	0.85	9.9	9.7
	Mitsubishi Chemical	Japan	85/17	91/13	127	147	0.67	0.62	0.65	0.96	7.6	7.7
	Sumitomo Chemical	Japan	78/18	73/16	173	156	0.45	0.47	1.17	1.29	9.2	8.1
COMPUTERS	IBM	U.S.	5561/1	4580/1	2927	2101	1.90	2.18	0.97	1.25	5.6	5.9
	NEC	Japan	2413/2	1794/2	2117	1390	1.14	1.29	0.72	0.72	4.9	5.0
	Hewlett-Packard	U.S.	1576/3	1124/4	1044	653	1.51	1.72	0.85	1.38	6.1	6.5
	Fujitsu	Japan	1496/4	1452/3	1236	1052	1.21	1.38	0.55	0.67	6.0	5.7
	Compaq Computer	U.S.	1133/5	991/6	426	354	2.66	2.80	1.19	1.18	4.6	5.8
	Hon Hai	Taiwan	1112/6	55/20	397	37	2.80	1.47	0.00	0.00	4.1	5.1
	Sun Microsystems	U.S.	1109/7	747/7	468	266	2.37	2.81	2.07	1.80	4.8	4.3
	Microsoft	U.S.	1028/8	721/8	357	211	2.88	3.42	3.07	2.18	4.3	4.5
	Cisco Systems	U.S.	911/9	123/19	133	25	6.85	4.94	1.15	0.90	5.8	4.9
	Xerox	U.S.	659/10	999/5	573	662	1.15	1.51	1.09	0.97	7.0	6.5
	Seiko Epson	Japan	569/11	365/11	409	242	1.39	1.51	1.27	0.82	7.0	7.2
	3Com	U.S.	509/12	158/16	178	48	2.86	3.28	0.38	0.76	4.7	5.2
	Ricoh	Japan	473/13	477/10	438	367	1.08	1.30	0.33	0.35	5.8	5.8
	Seagate Technology	U.S.	472/14	226/13	295	125	1.60	1.81	1.11	0.63	6.8	6.4
	OKI Electric	Japan	354/15	162/15	290	130	1.22	1.25	0.28	0.60	5.0	5.1
	Dell Computer	U.S.	266/16	246/12	94	88	2.83	2.81	0.06	0.10	4.9	4.8
	NCR	U.S.	233/17	225/14	142	137	1.64	1.65	0.49	0.67	7.5	6.6
	EMC	U.S.	210/18	157/17	87	45	2.41	3.51	1.33	1.77	5.4	5.5
	Apple Computer	U.S.	208/19	494/9	91	184	2.29	2.69	0.87	1.41	6.1	5.2
	Unova	U.S.	194/20	144/18	123	66	1.58	2.19	0.57	0.15	8.8	7.9
ELECTRICAL/ELECTRONICS	Canon	Japan	1977/1	1961/1	1938	1581	1.02	1.24	0.52	0.53	7.9	7.4
	Toshiba	Japan	1769/2	1413/4	1340	1104	1.32	1.28	0.68	0.65	5.8	6.0
	Sony	Japan	1694/3	1424/3	1436	1087	1.18	1.31	0.36	0.35	5.5	5.7
	Samsung	Korea	1602/4	1251/6	1571	1043	1.02	1.20	0.19	0.18	5.4	5.6
	Hitachi	Japan	1480/5	1569/2	1244	1198	1.19	1.31	0.67	0.82	6.8	6.6
	Matsushita Electric	Japan	1427/6	1265/5	1372	1081	1.04	1.17	0.50	0.66	6.1	6.0
	Siemens	Germany	1392/7	764/10	1497	878	0.93	0.87	1.11	1.01	6.9	7.2
	Mitsubishi Electric	Japan	1145/8	1190/7	1060	1044	1.08	1.14	0.53	0.77	6.0	6.0
	Koninklijke Philips Electronics	Netherlands	1078/9	893/9	1017	819	1.06	1.09	0.53	0.66	5.8	6.3
	Eastman Kodak	U.S.	777/10	894/8	883	885	0.88	1.01	0.29	0.38	8.0	8.2
	Sharp	Japan	742/11	566/13	640	483	1.16	1.17	0.83	0.84	5.4	5.5
	General Electric	U.S.	606/12	681/11	819	765	0.74	0.89	0.63	0.63	9.9	9.5
	Tyco International	U.S.	510/13	658/12	395	466	1.29	1.41	0.57	0.65	9.2	9.7
	Tokyo Electron	Japan	476/14	210/16	188	105	2.53	1.99	0.21	0.11	6.3	5.5
	Minolta	Japan	317/15	241/15	334	223	0.95	1.08	0.06	0.04	7.0	6.7
	Murata	Japan	285/16	177/18	303	181	0.94	0.98	0.24	0.24	7.5	7.6
	Sanyo Electric	Japan	254/17	190/17	257	186	0.99	1.02	0.29	0.57	5.7	6.1
	Brother	Japan	245/18	177/18	225	182	1.09	0.97	0.03	0.04	6.3	6.2
	Trimble Navigation	U.S.	217/19	146/20	85	49	2.55	3.00	0.19	0.26	6.7	5.4
	Raytheon	U.S.	216/20	299/14	227	302	0.95	0.99	0.56	0.86	8.3	8.2
	Emerson Electric	U.S.	196/21	139/21	213	178	0.92	0.78	2.22	1.04	10.9	10.2
	Alps Electric	Japan	193/22	90/22	205	94	0.94	0.96	0.03	0.07	5.7	6.2
SEMICONDUCTORS	Micron Technology	U.S.	3731/1	1276/2	1469	498	2.54	2.56	2.20	1.25	5.6	5.4
	Advanced Micro Devices	U.S.	2363/2	940/4	1055	395	2.24	2.38	0.75	1.13	4.9	5.1
	Intel	U.S.	1797/3	1432/1	813	523	2.21	2.74	0.82	0.90	5.3	5.0
	Taiwan Semiconductor	Taiwan	1383/4	349/9	514	159	2.69	2.19	0.28	0.28	3.8	4.2
	Texas Instruments	U.S.	1130/5	1007/3	729	626	1.55	1.61	1.87	1.28	6.7	6.5
	United Microelectronics	Taiwan	952/6	344/10	538	192	1.77	1.79	0.08	0.28	3.5	4.2
	LSI Logic	U.S.	770/7	466/6	325	197	2.37	2.37	1.06	1.78	5.0	6.0
	Hyundai Electronics	Korea	745/8	536/5	591	353	1.26	1.52	0.41	0.28	5.1	5.2
	STMicroelectronics	France	593/9	454/7	539	349	1.10	1.30	0.86	0.98	6.7	6.5
	Semiconductor Energy Laboratory	Japan	499/10	221/12	164	111	3.04	1.99	3.58	1.73	5.8	6.2
	Vanguard International Semiconductor	Taiwan	390/11	171/14	131	62	2.98	2.76	0.16	0.26	3.8	3.8
	Xilinx	U.S.	316/12	185/13	114	62	2.77	3.00	0.90	1.19	5.4	5.2
	National Semiconductor	U.S.	286/13	351/8	187	204	1.53	1.72	1.07	1.56	5.8	5.8
	Altera	U.S.	268/14	138/15	97	40	2.76	3.44	5.06	2.14	7.2	6.5
	Chartered Semiconductor	Singapore	261/15	53/18	79	25	3.30	2.07	0.14	0.22	3.5	4.5
	Lam Research	U.S.	228/16	67/17	81	29	2.81	2.28	1.42	0.80	6.6	6.3
	Cirrus Logic	U.S.	223/17	224/11	112	100	1.99	2.24	1.47	1.36	6.7	5.8
	Cypress Semiconductors	U.S.	188/18	130/16	113	64	1.66	2.03	1.42	1.06	5.6	5.2
TELECOMMUNICATIONS	Lucent Technologies	U.S.	2485/1	1701/2	1445	881	1.72	1.93	1.31	1.78	5.4	5.4
	Motorola	U.S.	2035/2	2148/1	1241	1193	1.64	1.80	0.63	0.76	5.4	5.5
	Ericsson Telephone	Sweden	1651/3	714/3	775	320	2.13	2.23	0.99	1.32	5.2	5.8
	BCE	Canada	1024/4	369/5	472	179	2.17	2.06	0.89	1.09	4.8	4.9
	AT&T	U.S.	875/5	566/4	343	135	2.55	4.18	1.07	1.12	4.6	4.8
	Nokia	Finland	630/6	259/8	306	163	2.06	1.59	0.49	0.53	5.3	5.3
	Alcatel	France	478/7	319/7	423	285	1.13	1.12	0.79	1.06	6.4	6.7
	Qualcomm	U.S.	451/8	350/6	111	63	4.06	5.56	0.71	1.47	6.7	6.4
	Verizon Communications	U.S.	375/9	147/11	93	74	4.03	1.99	0.73	1.75	5.9	6.1
	Cabletron Systems	U.S.	253/10	116/12	41	17	6.18	6.98	2.00	2.39	5.2	4.5
	MCI Worldcom	U.S.	216/11	193/10	82	63	2.64	3.05	0.99	1.13	4.7	4.6
	Nippon Telegraph & Telephone	Japan	168/12	204/9	127	120	1.32	1.70	2.04	2.15	4.6	5.0
	Ciena	U.S.	109/13	30/17	26	6	4.18	4.61	1.73	1.97	5.0	4.1
	JDS Uniphase	U.S.	100/14	57/15	52	36	1.93	1.61	2.21	1.31	7.1	7.5
	Qwest Communications International	U.S.	97/15	105/13	29	33	3.33	3.16	0.34	1.13	4.1	5.0
	British Telecommunications	U.K.	95/16	78/14	70	60	1.35	1.31	3.36	3.54	6.5	5.9
	BellSouth	U.S.	92/17	52/16	27	19	3.42	2.80	0.30	0.45	5.1	5.7

Indexing Innovation

Technology Review has teamed with CHI Research of Haddon Heights, NJ, to produce the Patent Scorecard, an industry-by-industry ranking of corporate patent portfolios. CHI combines the number of a firm's patents with other indicators to flesh out this deeper picture of innovation. Here are the specifics:

Technology Strength: This figure, the basis of the rankings, provides an overall assessment of a firm's intellectual-property power. It is calculated by multiplying the number of a company's U.S. patents by its Current Impact Index *(see below)*.

Number of Patents: The total number of U.S. patents awarded, excluding design and other special-case inventions.

Current Impact Index: This measure showcases the broader significance of a company's patents by examining how often its U.S. patents from the previous five years are cited as "prior art" in the current year's batch. A value of 1.0 represents average citation frequency; so 1.4 would indicate a company's patents were cited 40 percent more often than average, and so on.

Science Linkage: Patents sometimes cite scientific papers as prior art. This value shows the average number of science references listed in a company's U.S. patents. A high figure indicates the company is closer to the cutting edge than its competitors.

Technology Cycle Time: An indicator of a firm's speed in turning leading-edge technology into intellectual property, defined as the median age (in years) of the U.S. patents cited as prior art in the company's patents.

*average

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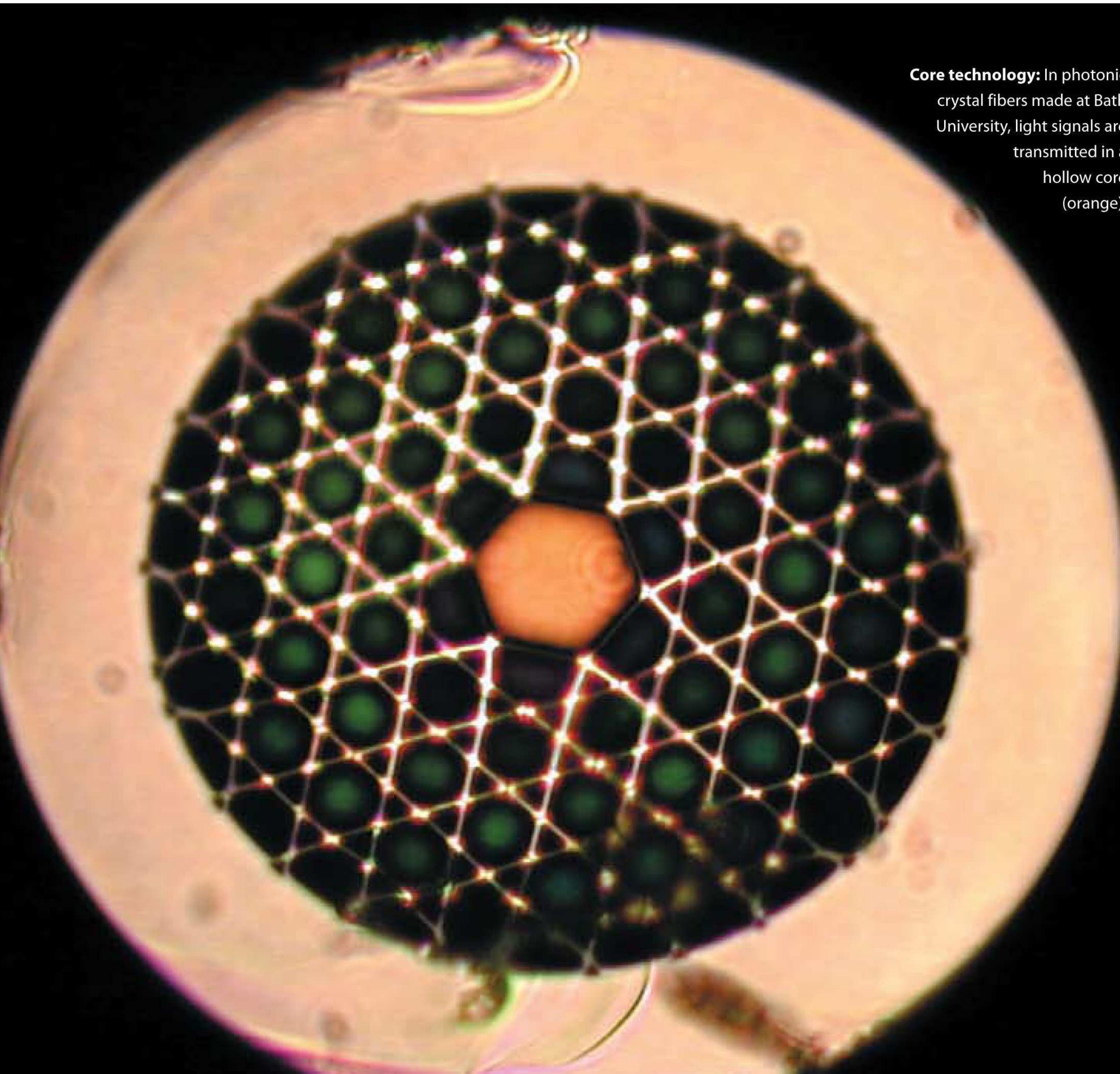


Core technology: In photonic crystal fibers made at Bath University, light signals are transmitted in a hollow core (orange).

The Next Generation of Optical Fibers

NEW MATERIALS PROMISE FAR MORE EFFICIENT LIGHT PIPES WITH A MUCH GREATER CAPACITY TO CARRY INFORMATION. IF THEY WORK, THE INTERNET WILL NEVER BE THE SAME.

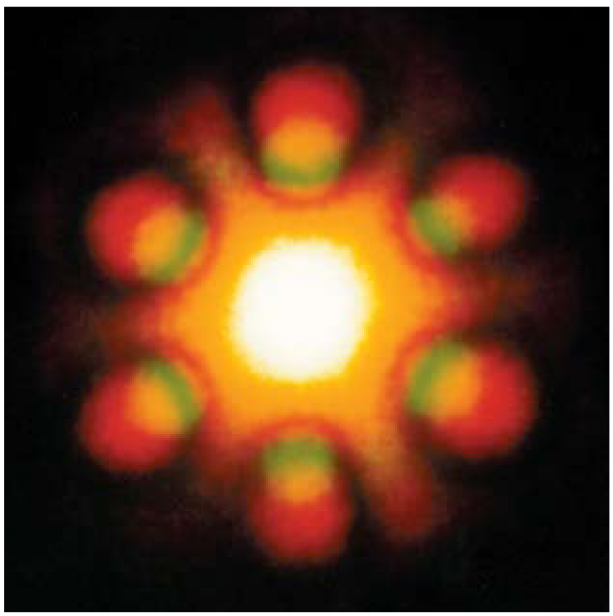
BY PHILIP BALL

COURTESY OF UNIVERSITY OF BATH

At first sight, these new materials are simply odd: thin as a hair, transparent and full of holes. Like the optical fibers that are the mainstay of the telecommunications industry, they're made of glass. But there the similarities with conventional materials come screeching to a halt.

The center of each of these novel fibers—which are made at the University of Bath, in England—is hollow. In existing optical fibers, light is transmitted through a glass core. In the fibers made at Bath, light travels unhindered through air. The light beam is confined to the hollow core by the holes in the surrounding glass material, which looks like a honeycomb in cross section and creates a strictly no-go region for light. The ability to confine light in air this way, says Philip Russell, a Bath physicist, "could completely revolutionize telecommunications."

The reason for the excitement is that, in principle at least, sending light through air rather than through glass could greatly increase the efficiency and capacity of today's high-speed telecom networks. These new materials, called photonic crystal fibers, should "leak" less light and carry more intense light pulses without distortion, reducing the need to constantly boost a signal—an expensive chore in today's optical networks. Photonic crystal fibers should be able to convey much more information along fiber-optic networks while lowering installation and maintenance costs. They will be to existing fibers as a 10-lane freeway is to a country lane. Not only will they take more traffic, but the journey will be smoother and there will be less need for refueling.



PHOTOGRAPHS COURTESY OF UNIVERSITY OF BATH

It is still early in the development of this new generation of optical fibers. Even the most advanced of the new materials remain several years from widespread commercial use. But with so much at stake—optical telecommunications is a multibillion-dollar business—several industrial labs, including Corning and a handful of startups, are in hot pursuit of their own versions of photonic fibers. While it's too soon to predict which will prevail, rival approaches developed at the University of Bath and at MIT are already competing head-to-head to become the optical fiber of tomorrow.

These efforts may bear fruit just in time for the telecommunications industry. The huge expansion of long-distance optical data transmission in recent years, fed by the growth of the Internet and its bandwidth-hogging applications, has led researchers to find ways to shoot more light and more complex signals through optical fibers *(see "Wavelength Division Multiplexing,"* TR *March/April 1999)*. But many experts believe that in the coming decades it will become impossible to squeeze any more performance out of the current generation of glass fibers. Although it's difficult to predict exactly when the roadblock will be reached, Jim West, a scientist at Corning's research laboratories in New York, definitely believes "we'll run into those limits." And that's when the next generation of fiber optics will become crucial in feeding the world's apparently endless appetite for bandwidth.

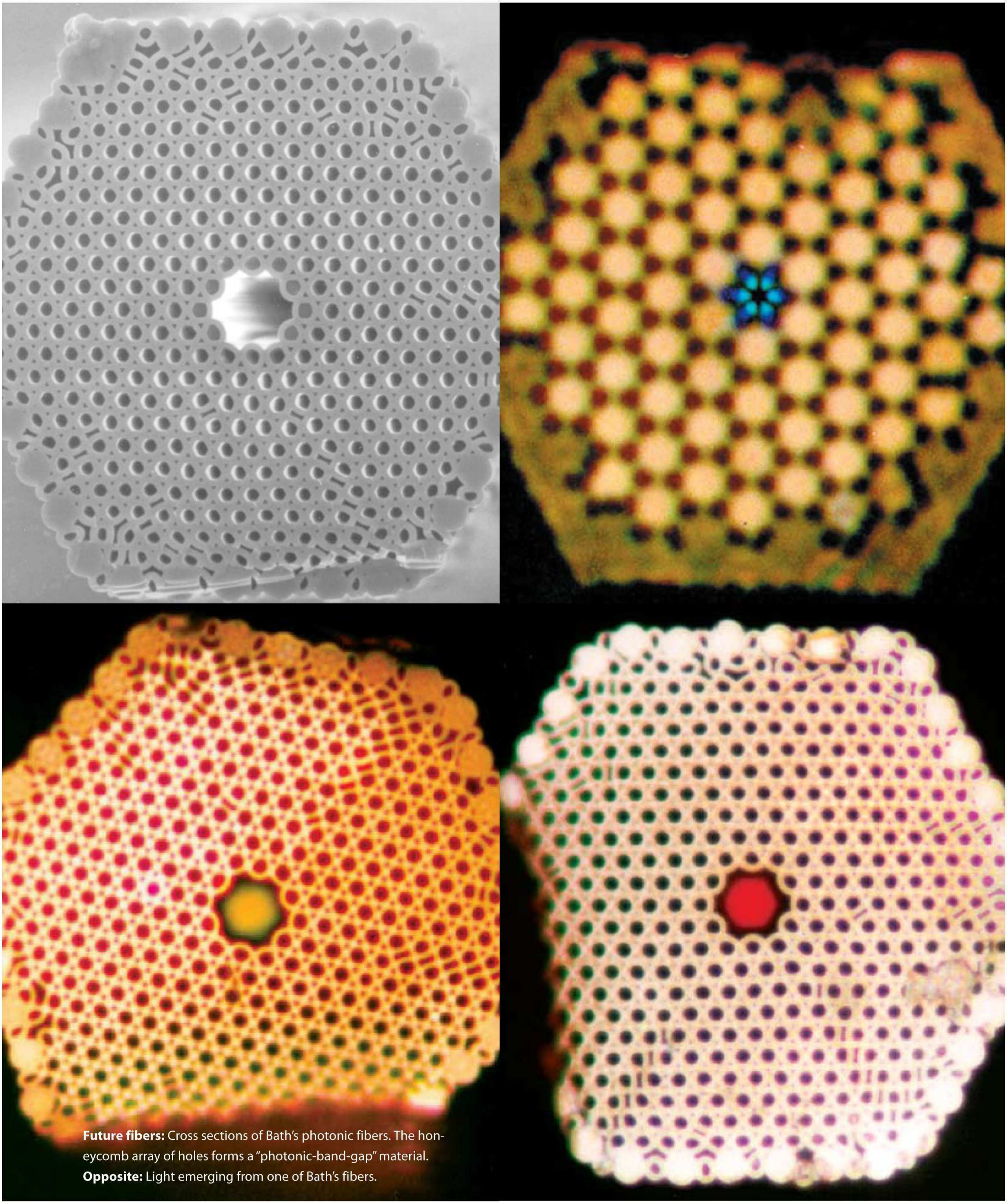
Light Conversation

Although photonic fibers are a next-generation technology in 2001, the history of conveying voice data using light extends back more than a century. After inventing the telephone in 1876, Alexander Graham Bell didn't rest on his laurels. In 1880 he showed that light, rather than electricity, can carry a person's words to a distant ear. Bell's "photophone" used vibrating mirrors to transmit sound via sunlight. But it was an idea long before its time. Sending electrical signals down copper cables proved much more reliable, and the photophone was largely forgotten as telephone lines enmeshed the world.

After eight decades of the supremacy of copper wire, the invention of the ruby laser in 1960 put light back on the communications agenda. Here was a source bright enough to really put light to work. Just as the transistor ushered in the age of microelectronics, the laser sparked the age of photonics. In 1970 Corning proudly announced that it had sent a laser beam down a glass fiber and recovered as much as one percent of the light at the other end, a kilometer away (today's glass fibers are so efficient that 80 percent of the light will survive that distance). By the 1980s, telephone companies began replacing copper cables with optical fibers.

An optical fiber can carry thousands of times more data than a copper cable: in principle, a single fiber can transmit up to 25 trillion bits per second. That's enough capacity to carry all the telephone conversations taking place at any instant in the United States—with room to spare. Small wonder that the worldwide web of information technology is being woven from light-bearing glass.

In a conventional optical fiber, light is confined in a silica inner rod by a "cladding" of glass with a slightly different composition than that of the core. Typically, small amounts of germanium or phosphorus are added to the core (a process called "doping"), giving it a different refractive index from the cladding.



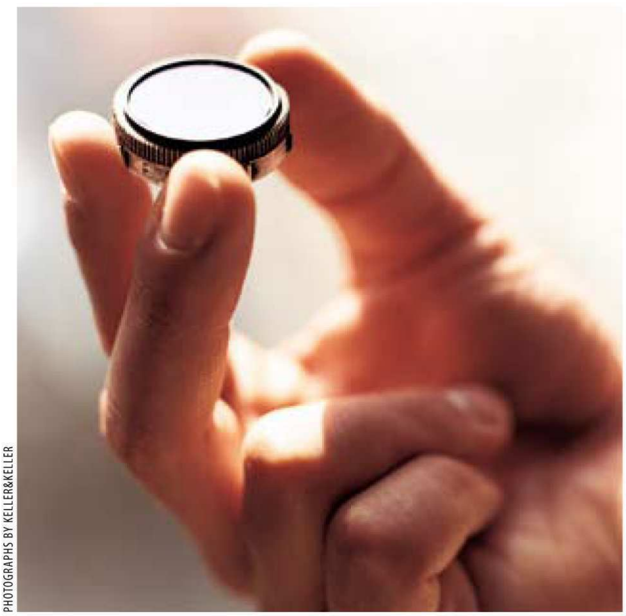
Future fibers: Cross sections of Bath's photonic fibers. The honeycomb array of holes forms a "photonic-band-gap" material. **Opposite:** Light emerging from one of Bath's fibers.

Guiding light: A prototype fiber in which the hollow core is lined with a "perfect mirror" made at MIT. Opposite: A sample of the original perfect-mirror material made by Yoel Fink and his MIT coworkers.

Light striking the interface between core and cladding is reflected, so the signal bounces back and forth and remains within the core. Information is encoded in a series of pulses from electronically controlled lasers and fired down the fiber to a photodetector at the other end, which converts the signal back into electrical form for processing in a telephone, computer or routing device.

Sounds great. So, where's the catch? It's a matter of limits. As communications networks get bigger, busier and more ambitious, the drawbacks of conventional glass fibers are becoming evident, and existing optical-fiber networks will eventually be unable to cope. One factor that limits performance is the fading of the light signal over distance. A certain amount of the light is "scattered"—impurities in the silica disrupt the transmission of some of the signal—as it travels through the glass core; other light simply escapes from the fiber altogether, because the interface between glass core and cladding is not a perfect mirror.

Unremedied, these losses would cripple long-distance fiber-optic communications: eighty percent transmission over a kilometer would leave less than a ghost of a signal at the far end of a transatlantic cable. The answer is to amplify the light every 70 kilometers or so. But amplifiers are expensive, and they require their own power sources *(see "5 Patents to Watch: Booster Shots," p. 44)*. Each amplifier typically adds a million dollars to the price of a long-distance transmission line. For a cable thousands of kilometers long, that begins to add up to real money. And when an amplifier breaks down mid-Atlantic, there's no option but to send out a ship to dredge up the cable. "It costs a fortune to fix them at the bottom of the ocean," says Bath's Russell.


PHOTOGRAPHS BY KELLER&KELLER

This daunting economic reality is the spur for developing the new generation of fibers. Cambridge, MA-based OmniGuide Communications, founded last year by several MIT professors, claims its new fibers will be able to squeeze losses so low there would be no need for any amplification. What's more, the company says, the usable bandwidth will be substantially larger than in existing optical fibers. The trick is to strip out the fiber's glass core and replace it with—well, nothing at all.

Pure Air

It sounds so obvious. Light travels through air with little scattering. So why not just send laser light down a hollow glass tube? The answer lies in physics. To achieve the internal reflection necessary to keep light confined in the center of a conventional optical fiber, the cladding has to have a lower refractive index than the inner medium. But all known materials have a higher refractive index than air. So the conventional arrangement doesn't work in making a hollow fiber.

Which means an unconventional approach is needed. Enter photonic crystal fibers. Researchers worldwide are busy making materials that act as "light insulators," which are impassable to light just as most plastics are impassable to electrical currents. In the jargon of physics, these light insulators have a "photonic band gap" corresponding to specific wavelengths of light; those wavelengths simply cannot enter the material. If made correctly, these materials—unlike the cladding in glass fibers—should permit virtually no light to escape from an empty core wrapped in them.

Of course, many substances will stop light from passing through; but this is generally because the materials simply absorb the light rather than reflecting it. And while you might think of metallic mirrors—silvered glass—as good light reflectors, the truth is that they are not nearly reflective enough to work in fiber optics; they absorb and dissipate a small but significant part of an incoming beam. A light signal traveling down a silver-lined glass tube would travel only a short distance before dispersing entirely. Photonic-band-gap materials, on the other hand, block all photons of particular wavelengths; the oncoming light is reflected almost perfectly. In other words, they are just the thing for confining light inside a hollow tube.

In 1998, Yoel Fink, then an MIT graduate student, fabricated a "perfect mirror" out of a photonic-band-gap material. Others had previously made specialized mirrors from thin layers of dielectric materials (materials that contain electrically charged particles but have insulating properties). These mirrors have photonic band gaps, and can be extremely efficient reflectors, but they have a major flaw: they work only with light striking absolutely face-on, limiting their use to specialized applications. Fink figured out how to make a version of a dielectric mirror that reflects light coming at it from all angles, as the material would have to in the core of a fiber-optic thread.

Once you have such a mirror, seeing the commercial potential is (for photonics researchers, at least) obvious. Fink and a pair of his MIT professors, physicist John Joannopoulos and materials scientist Edwin Thomas, along with Uri Kolodny, cofounded OmniGuide. The company's goal is to use the perfect mirror as cladding for an optical fiber. Imagine taking a flat mirror and bending it around the inside of a tube, and you have a crude picture of an OmniGuide fiber.

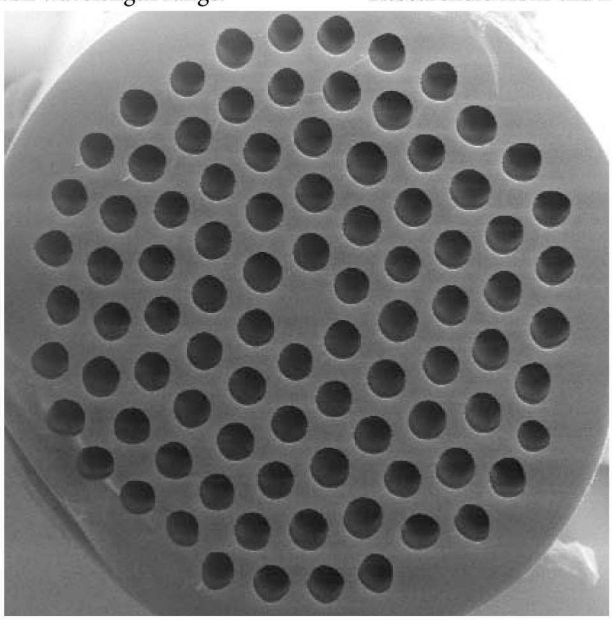
So just how small are the losses of light in such a next-generation fiber? Because the company is still in its early stages, the founders are keeping that information close to their chests. "All I am free to say at this stage," says Joannopoulos, "is that with a hollow-tube OmniGuide [fiber] we could in principle achieve losses less than optical fiber." But for a telecom industry looking to push more and more light through optical networks—and eventually facing the limits of current-generation fibers—even such carefully worded pronouncements are tantalizing.

The company is developing a series of fiber products based on the OmniGuide concept. These fibers are, in theory, far more

efficient in transmitting light than a standard optical fiber. Indeed, they should be able to overcome the current limitations of glass fibers, achieving, among other things, less signal loss as the light travels down the fiber. Such heightened performance is possible, says Fink, now an assistant professor of materials science at MIT, "because we can achieve an unrivaled degree of confinement."

The OmniGuide fibers should be able to convey much more intense signals than normal optical fibers. High-intensity light traveling in glass fibers suffers from distortions that can disrupt the transmission of signals at different wavelengths, causing cross talk between channels unless they are widely separated in frequency. This effect limits the number of different wavelengths you can stuff in a conventional glass fiber, and also how bright they can be. Because signals in air don't suffer these effects, Fink explains, the OmniGuide fiber can convey signals at higher powers, with channels spaced closer together. That is great news for telecom companies, since stronger signals travel farther before losses begin to compromise them, and closer channels mean that more data can be packed within a given wavelength range.

The MIT approach, however, is only one way to make a photonic fiber. Other researchers have produced photonic-band-gap materials that, in cross section, are like a honeycomb in which the holes form structures that refuse entry to light of certain wavelengths. These kinds of photonic crystals, first made in the late 1980s, also nearly totally block out light. The glass fibers made at Bath, for example, are penetrated by an orderly array of holes running parallel to the thread along its entire length; at the center is an empty core in which light can be nearly perfectly confined. To give some indication of the precision involved in making the fibers, if the long, parallel holes were the diameter of the Chunnel connecting England and France, the experimental fibers made at Bath would reach Jupiter. How does one drill such perfect tunnels through a glass strand thinner than a human hair?



PHOTOGRAPHS COURTESY OF CRYSTAL

Fortunately, the holes don't have to be drilled at all. They are ingeniously constructed by drawing the glass fibers from a bundle of hollow capillary tubes. The tubes are packed together in a hexagonal array a few centimeters in width, and the bundle is heated to soften the glass. As the array is pulled out into a fine fiber, its cross section gets shrunk by a factor of a thousand or so but remains laced with holes.

Initially, the Bath physicists made a light-conducting channel at the core of the fiber by substituting a solid glass rod for the central glass capillary. But still better than carrying the light in a solid core would be to send it through a hollow core—through air, with the very low losses and absence of distortion that entails. In collaboration with Douglas Allan, a researcher at Corning, the Bath team succeeded in achieving light confinement in a hollow-core photonic crystal fiber in 1999. Recently they have formed optical fibers many meters long out of their novel materials.

Photonic Finish

Taking on existing optical fibers will be a tall order. Conventional glass fibers have been optimized over several decades and are made using well-entrenched technology. In contrast, the new photonic fibers represent a manufacturing unknown. For one thing, their structure must be exact. "The existing [fabrication] systems are simply not up to it," admits Russell.

Still, companies are lining up to meet the commercialization challenges. Fink says OmniGuide is working on a series of products based on different-length fibers. Projects include the development of active fiber-based devices for optical switching, as well as the development of fibers for light transmission over 10 to 100 meters, which could be useful for tasks such as connecting servers over short distances. Long-haul fibers for telecom networks will have the biggest impact, says Fink, but these "will take a little time."

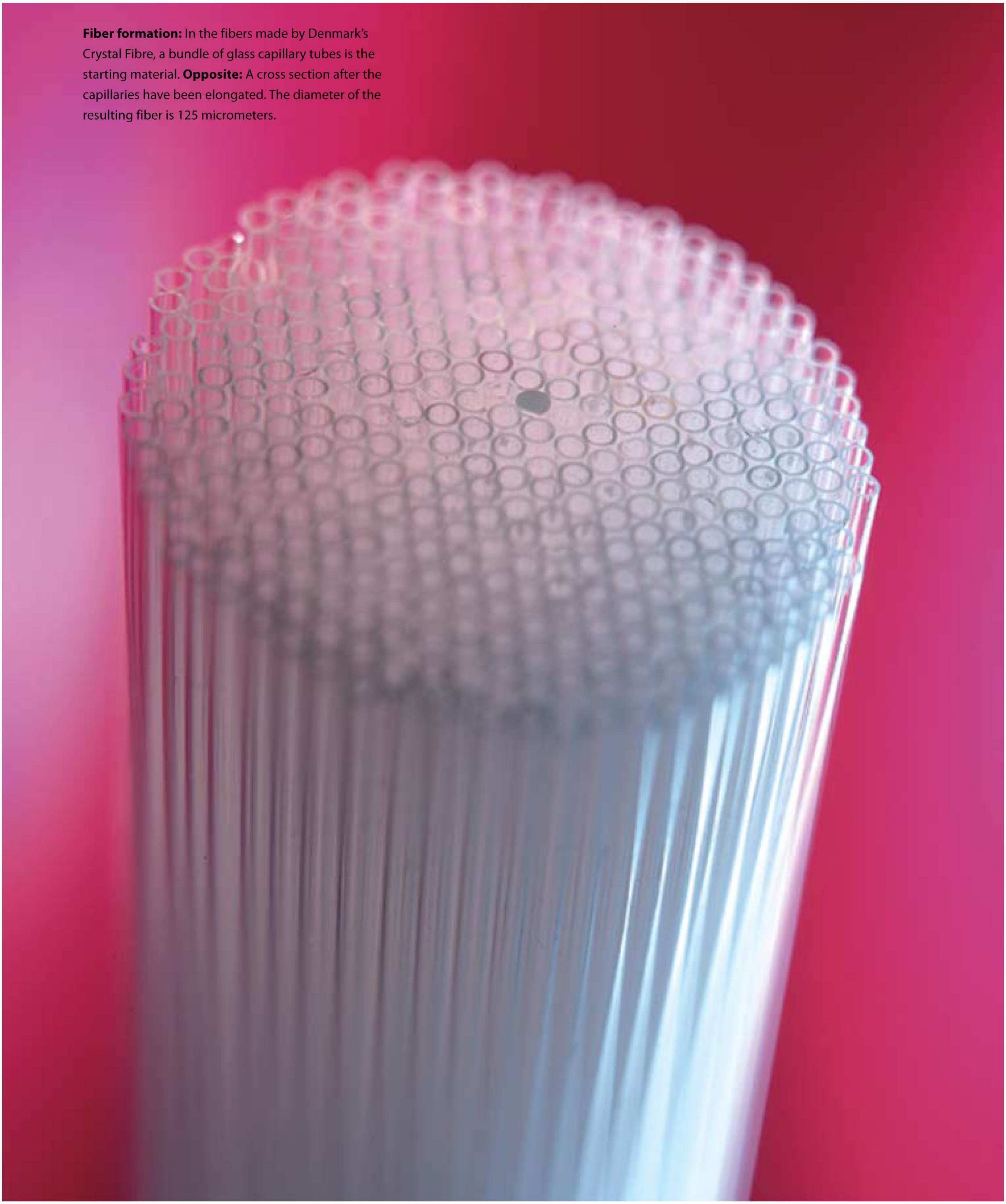
Researchers from the Bath group have launched their own spinoff, BlazePhotonics, and have secured funding from venture capital firms in the United Kingdom and United States. In Denmark a company called Crystal Fibre, started by scientists at the Technical University of Denmark in Lyngby who were early collaborators with the Bath group, is making photonic fibers with a solid glass core. While its initial products might serve such purposes as confining light in high-precision lasers, no one is losing sight of the big prize. "Telecommunications is definitely the medium-term target," says CEO Michael Kjaer.

Like the founders of Denmark's Crystal Fibre, scientists at Corning have worked closely with the Bath researchers in the past, but they are now racing to the marketplace on their own. Jim West reports the company can now make photonic fibers up to a hundred meters long. But he reserves judgment about whether the new materials will eventually transform the information superhighway. Conventional optical fibers, he points out, are a difficult act to top. "It's only when you start working with the state-of-the-art versions that you realize how remarkable they are."

Although sending light through air may solve many of the limitations of today's fibers, it poses its own problems. For one thing, the composition of air is not uniform; as a result, light may be transmitted differently in different parts of the world. "Air in the U.K. is very different from air in the Sahara," explains West.

"It's a fascinating technology," says West of the new generation of photonic crystal fibers, "but there is a long way to go."

Still, if these new materials eventually fulfill their potential of transforming long-distance transmission in the telecommunications industry, it will be a journey well worth taking. ◊



Fiber formation: In the fibers made by Denmark's Crystal Fibre, a bundle of glass capillary tubes is the starting material. **Opposite:** A cross section after the capillaries have been elongated. The diameter of the resulting fiber is 125 micrometers.

In 1969, we worked on a SECRET GOVERNMENT PROJECT *that became the Internet.*

OHHH, SO THAT'S WHY NOBODY KNOWS WHO WE ARE!

Back in the '60s a small band of computer whizzes was hired by the Department of Defense to work on the ARPAnet. Or what is commonly known as the forerunner to the Internet. These visionaries came from the legendary research and development company, BBN.

Government work being what it is, there wasn't a lot of publicity about this.

Their work did, however, yield many firsts. The first router. The first e-mail message. The first network packet encryption technology and more.

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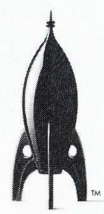
Spun off from GTE last year, this powerhouse of Internet services is known today as Genuity.™ With Data Centers strategically located around the world and Network Operations Centers continually monitoring security and bandwidth for serious eBusinesses everywhere.



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A BRIEF HISTORY

BBN

In 1969, BBN was hired by the U.S. government to develop the ARPAnet, the forerunner of the Internet.

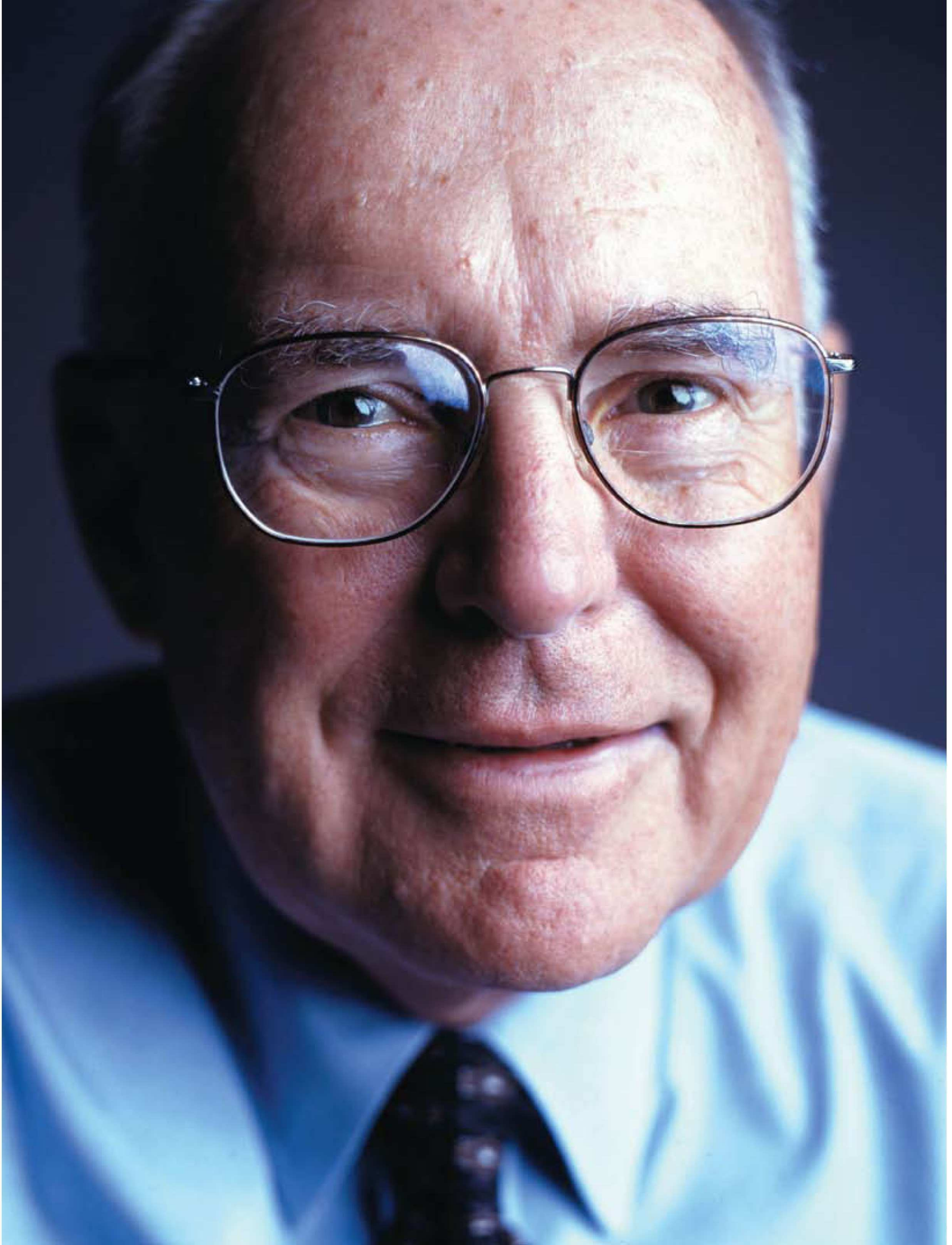
GTE INTERNETWORKING

In 1997, BBN was acquired by GTE, the company that created our high-speed, 17,500-mile, Tier 1, fiber-optic network.

GENUITY™

In 2000, GTE Internetworking became an independent company, renaming itself Genuity. Today, Genuity offers a vast array of managed Internet services, including Black Rocket.™

GENUITY™



Q & A

LAYING DOWN THE LAW

At 72, Intel cofounder Gordon Moore has "gone fishin'"—if you don't count looking for aliens and launching a $5 billion foundation to back far-out research and protect the environment.

Gordon Moore is most famous for coining Moore's Law, his 1965 prediction that the number of transistors that could be packed into an integrated circuit would double every year. A decade later, he revised that estimate to every two years—a prediction that has held remarkably true ever since and is often used as a baseline for evaluating performance in other spheres of computing. But the semiconductor pioneer and cofounder of Intel claims he has never really been good at predicting the future. In fact, he says he's pretty bad at it.

FERGUS GREER/ICON INTERNATIONAL

In a wide-ranging conversation from his vacation home on Hawaii's big island, this 72-year-old avid fisherman and pragmatic environmentalist spoke with *Technology Review* editor at large Robert Buderi about the future of Moore's Law, which he's revising again. He also discussed the newly created Gordon E. and Betty I. Moore Foundation, which he plans to endow with $5 billion worth of Intel stock (about half of his estimated wealth). The new foundation will be geared to supporting far-out university research and advancing programs that protect the environment.

Finally, Moore reveals why he and a few pals named Hewlett and Packard picked up the tab for the Search for Extraterrestrial Intelligence—and shares how it's possible to succeed wildly in business without having a crystal ball.

TR: Where do you think we are heading technologically? What excites you most?
MOORE: I calibrate my ability to predict the future by saying that in 1980 if you'd asked me about the most important applications of the microprocessor, I probably would have missed the PC. In 1990 I would have missed the Internet. So here we are just past 2000, I'm probably missing something very important.

Certainly the things going on in molecular biology these days are exciting. We really are understanding increasingly how all the life processes work. In the information sciences, the increasing capability of networks is changing the way we do everything. It's going to result in all of us having a lot of bandwidth whenever we want it, to go with a lot of computing power. As far as what are we going to do with all the computing power, I'm sure I'll miss the most important things. But the one capability that to me will make a qualitative difference in how we do things is truly good speech recognition. That is, a machine that can recognize if you mean t-o, or t-w-o, or t-o-o by understanding in context what you're saying.

Once a machine understands in context like that, you can actually hold an intelligent conversation with a machine. That will dramatically change the way people interact with machines—and broaden the number of people that can use them. I have no idea how far away that is. At the level I'm talking, it's probably 20 to 50 years away. But there's certainly nothing impossible about it.

TR: What about the future of Moore's Law?
MOORE: We're at a time where we're kind of doubling about every two years, which is where we've been for the last 25 years. But sometime probably between 2010 and 2020, we lose the largest single factor that lets us continue on that curve—our ability to make things smaller [*For a complete look at this issue and possible future computing technologies, see* TR *May/June 2000*]. You run into the problem that materials are made of atoms, and we're getting down to small enough dimensions where they no longer behave like bulk materials. So we'll have to depend on other factors to continue on this curve. And that means finding better ways to pack things. Some people are talking about moving into the third dimension. A little bit of that has been done. You could also make bigger chips, losing some of the economic advantages. But maybe the doubling time will change from every two years to every four or five years. It's not the end of progress by any stretch of the imagination. We'll be putting a billion transistors on a logic chip; it'll keep designers busy for decades figuring out what they can do with that.

What's going to replace our technology? I'm a skeptic that anything is. It's the other way around: our technology is finding its way into a variety of other fields. I view the integrated-circuit technology as the way you make complex structures of materials layer by layer. We got the biology industry making their gene chips using our technology, and all these little MEMS, or microelectromechanical systems. This technology is just very versatile in making these microstructures, and I don't think it's likely to be replaced by something else.

TR: What concerns you most about the technological road ahead?
MOORE: One concern I have is the rate at which the U.S. is training engineers. We are squandering a good portion of our lead in the world by not training enough of our people so that they can be major participants in industry. There are really good jobs that are going begging, and many of them are getting exported. Intel has technical operations in China, Russia, India and so forth, and we have them there frankly to a significant extent because that's where there are trained people. I guess I'm still sufficiently U.S. oriented that I cringe to see the quality of jobs we're exporting overseas.

TR: Does that mean we haven't motivated people in this way?
MOORE: That's exactly what it means. Frankly, our schools K through 12 have not done a good job with the basic programs necessary to motivate people in the direction of a technical career. Technical careers start early. I don't think you can wait until people start college to convince them they ought to become engineers, if they don't know how to multiply and divide. I know in my case I knew generally the direction I wanted to go in before I started high school.

TR: But with the foundation, you didn't want to get into K through 12 education, to try to promote more people to go into engineering?
MOORE: Not unless we had some special new idea for doing it. So many people are tackling it in so many ways, it's awfully hard to know how to do something different and have an impact. It's kind of like solving world hunger, the way I look at it.

"I CALIBRATE MY ABILITY TO PREDICT THE FUTURE BY SAYING THAT IN 1980 IF YOU'D ASKED ME ABOUT THE MICROPROCESSOR'S MOST IMPORTANT APPLICATIONS, I WOULD HAVE MISSED THE PC."

FERGUS GREER/ICON INTERNATIONAL

TR: So instead the foundation focuses more on higher education and science. What were your motivations for starting it, and what do they say about the role of government in funding scientific and technological research?
MOORE: The way research is funded in the U.S., with peer review and government projects and the like, does a very good job on the mainstream. Established scientists who are in the system continue to get support. It's a lot harder for unusual, possibly harebrained ideas to get funded. Those don't do so well in peer review, typically; and new people trying to get

away $100 million in $20,000 grants. We would be much more likely to look at the needs of an entire school, rather than trying to do individual projects.

TR: What has you concerned about the environment, and how do you plan to address those concerns?
MOORE: Ed Wilson [Edward O. Wilson of Harvard University] tells me that species are disappearing faster now than they have at any time since the demise of the dinosaurs. You can just see whole areas, whole ecosystems being destroyed. This will make the world a very much less interesting place, and very likely a much less resilient place. We won't be able to recover from some of our disasters, perhaps.

The world is changing rapidly, and wild places are disappearing. For example, I used to go to Baja California a couple of times a year when it was remote and unspoiled. Now you see what's happened to Cabo San Lucas compared to what it was like in the early '60s. It's a lot of hotels and golf courses. It's Cancún on the end of Baja.

I've been involved in an organization called Conservation International that focuses on preserving biodiversity. Where people are not especially well established, getting major areas set aside as preserves is one thing they're doing. There are really a few major tropical wildernesses left, and that's appropriate there. But in the so-called hot spots—the Atlantic Forest in Brazil, the Mayan area in Guatemala and Mexico, Madagascar—they work a lot with the local people. Getting local interest and local capacity in conservation is extremely important. But we have to help develop ways to get as great or greater economic value for the local people from leaving the forest standing—say for harvesting Brazil nuts—than chopping it down for a one-time benefit.

In Peru, Conservation International worked with Mobil, which was exploring there, to come up with best practices that would have a minimum impact on the forest and the native people. Such things as instead of building roads, you fly in with helicopters, because roads turn out to be the source of a lot of the destruction of the forest. Once there's a way in, it's a route that people tend to migrate out and cut things down next to—the culture just spreads in. So flying in with helicopters avoids that. And it made a significant

started, or established scientists trying to change fields, have trouble getting support. So I hope we'll be able to find some projects like that—some of which will be complete failures, but a few of which I hope will open up some new areas.

TR: Was there any particular event that spurred your thinking along these lines?
MOORE: Nothing in particular. But, for example, I've given small amounts of money to the Division of Geological and Planetary Sciences at Caltech. For a few tens of thousands of dollars, some professors there have been able to try something that would have been hard to fund conventionally, and get some very interesting preliminary results that they can use as a basis to get more conventional funding. One was wanting to study the dust coming in from outer space. Evidently a moderate amount of the dust that falls around is that, and it can be determined by looking at the ratio of the helium isotopes. This professor [Kenneth A. Farley] started out to collect the crud falling in Pasadena to see if he could separate out the dust coming from outer space as opposed to local sources. And he was very successful. It certainly led to enough preliminary information that he had the ability to go in for a federal grant, and I believe he got one.

I think similar kinds of things can happen pretty broadly at any of the good schools. I'll have to admit to being a bit of an elitist. I think the elite institutions do a disproportionately good job with their research and education. And if anything, the government would like to make things more uniform—to try to spread funds fairly uniformly across the country. There's probably a very important social aspect in doing that. The federal government clearly can't give all of its support to Caltech and MIT. But I lean toward making the best even better. We don't want to build the infrastructure necessary to give

contribution, so that the exploration was carried out with really a minimum impact.

We will certainly look more broadly than one organization. So far Conservation International has been confined mostly to terrestrial ecosystems—that's looking at something less than a third of the world. There's a lot of oceans out there that could benefit from a similar approach, and we'll have to see how else we can get ahold of the problem. But the idea of biodiversity is a pretty good peg to hang the program on.

TR: You worked on George W. Bush's technology advisory committee during the campaign. Is the environment something you plan to be active on with the new administration?

MOORE: It's awfully early to judge if Bush is going to be reasonably friendly to the environment or not. You can see some things already where he had opportunities to make significant changes in a negative way and passed them up. The area that Clinton designated a protected area, or not quite a protected area—all of the western Hawaiian island chain, starting beyond Kauai, and all the way up through Midway—mostly uninhabited reefs and rocks such as the French Frigate Shoals and the Gardner Pinnacles. Bush could have rescinded the order and didn't.

But conservation doesn't mean putting a fence around everything and keeping people out. You have to come up with ways that people can live with the environment while making as little negative changes as possible. Environmentalists run the spectrum from the very radical—you can't touch anything—to those who take a much more pragmatic view of it. I'm probably toward the pragmatic end of things. And I don't have any reason to believe that the new administration won't take a somewhat similar point of view.

TR: Although this is outside the foundation, for years now you've supported the Search for Extraterrestrial Intelligence. Why? Do you expect there is intelligent life out there?

MOORE: SETI is a far-out program that potentially could have a very profound impact on everybody on earth. I was amazed when it got dropped out of the NASA budget. Some senators started laughing about little green men, and NASA just wouldn't touch it again. So I got involved in keeping the thing going, with Bill Hewlett and Dave Packard—we each committed to support it for five years—and [Microsoft cofounder] Paul Allen came in and did part of it. I was hoping that NASA would wake up and get it back into their program by now. Unfortunately, there doesn't seem to be any movement in that direction.

My view is statistically it's likely that there is intelligent life someplace else in the universe. If you look here on Earth, where there have probably been a billion species since the beginning, only one of them has become intelligent—so your first-order estimate is a chance in a billion of that happening for a single species. But there's something like a hundred billion galaxies, each with a hundred billion stars. Even a small probability multiplied by 10^{22} gets pretty big.

"IT'S LIKELY THAT THERE IS INTELLIGENT LIFE SOMEPLACE ELSE IN THE UNIVERSE. THAT INTELLIGENCE COULD BE TRANSMITTED TO EARTH. WE MIGHT MAKE HUGE LEAPS IN A SHORTER TIME."

If it's close enough for us to ever hear from or not is a much longer shot. But I think it's very well worth a concerted effort to look for. Potentially, it could make a huge advance for us. You could argue that anybody out there that we happen to find has probably been around at the level that they could communicate much longer than we have. So they're probably significantly more advanced. Presumably, that intelligence could be transmitted from whomever we find to Earth. We might be able to make huge leaps in a shorter period of time.

TR: That would be something. But for now, we're stuck with ourselves—and the experience of people like you. Do *you* have any advice, say, for hopeful entrepreneurs?

MOORE: I've only seen a couple of ideas in my career that I thought were sufficiently different that I was comfortable considering starting a company on. And clearly, every opportunity doesn't justify it, as we proved experimentally over the last couple of years. So the only advice I'd have for them is to really understand what your market needs and what your advantages are.

TR: You started by mentioning you weren't very good at predicting the future. What's your closing advice on how start-ups, or any company, can achieve success without the ability to perceive how things will shake out?

MOORE: First, surround yourself with the best people you can possibly find. And try to anticipate general directions things are going in. When Intel was set up, we really wanted to get a guy with a lot more knowledge of digital systems than we had: we were all components people. So we hired Ted Hoff, a postdoc at Stanford. Ted had done quite a bit with computer architecture and the like.

After we did our first memory chips we were looking for other large-volume applications of complex circuits. That was when electronic calculators were just coming in. So we started looking for a calculator company to work with. But established semiconductor companies had already made deals with the existing calculator companies, and the only one we could find was a Japanese startup by the name of Busicom that wanted to make a family of business and scientific calculators. They had designed some 13 complex custom chips—and wanted us to make those for them.

Well, we could no more take on 13 complex chips than *fly* with our little engineering group. And Ted Hoff looked at them and said, "Gee, we could do all of these calculators with a general-purpose computer architecture—and I don't think the processor would be more complex than the memory chips we're making." He saw it as an embedded controller very generally. And we said, "Ah, that's the kind of thing we're looking for, a general-purpose complex chip." And so we convinced the Japanese company to throw away all its designs and start over with our approach—and that was the origin of the microprocessor. Having looked ahead and hired Ted Hoff, who had knowledge in areas that we really didn't, was absolutely key to doing the microprocessors.

And that's the kind of thing one has to do in order to be ready for what comes along. ◊

The ABC's of Safety: Air bags. Buckle up. Children in back. *At maximum output.

ENGINEERED TO BE ALMOST PSYCHIC.

Introducing a car so technologically advanced, it can sense trouble and begin to adjust for it before the driver even notices that there's a problem. It's the 6-cylinder 212-horsepower Outback VDC from Subaru. The VDC stands for Vehicle Dynamics Control, a highly intelligent stability system that rivals those found in vehicles costing thousands more.

Using a sophisticated series of sensors, VDC can help prevent loss of control due to oversteer, understeer, wheel spin or vehicle drift. The instant a difference is detected between the driver's intended direction of travel and the path the car is actually taking, VDC takes corrective action. Momentary brake pressure may be applied to individual wheels. The All-Wheel Drive system may redistribute the amount of power between the wheels. Even the engine's output may be momentarily reduced. Before the driver even realizes that loss of control is impending, any or all of these measures may be applied automatically to help restore directional stability. It's almost as if the car has a sixth sense.

In fact, in every sense the Outback VDC is a remarkable vehicle. It even features a state-of-the-art 200-watt* sound system built exclusively for Subaru by McIntosh®. With 11 speakers placed in 7 strategic locations, the audio quality has been specifically tuned to the car's unique acoustics.

The Outback VDC from Subaru. Truly a phenomenon in the world of automotive engineering. To find out more, visit us at **www.subaru.com**.

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POWER TO THE PEOPLE

Fuel cells and microturbines could turn everybody into a power producer, easing blackouts, lowering prices and bringing electricity to the powerless.

BY PETER FAIRLEY

It's mid-afternoon in sunny California and your team is scrambling to finish a deal-clinching presentation when BAM! the power goes down. You've been caught in a rolling blackout that state regulators have ordered as a heat wave brings on millions of air conditioners. Backup batteries will give you enough time to shut down your system, but you can forget about finishing that presentation. Lights out, right?

Not when a pair of refrigerator-sized turbines in back of your office jump to life, transforming natural gas into a steady stream of electrons to keep the office humming. Systems like these "microturbines," along with fuel cells that extract electrical power from fuel without burning it, are changing the rules in the power game. No longer must you rely on a monopolistic utility that can take you—and your power needs—for granted.

These "micropower generators" aren't just about emergency backup, either. They can provide higher quality power 24/7 than you can buy from your local utility. Plug into one of these systems and you'll avoid the computer-crashing voltage spikes and sags that mar the electricity coming out of a garden-variety wall socket. And micropower means you can forsake the grid when power prices surge, or even make an extra buck by exporting power to your neighbors. Spread enough micropower throughout the grid, and the grid itself will begin to learn tricks that could make regionwide power outages an unpleasant memory.

PHOTOGRAPHS BY SIAN KENNEDY

PREMIUM JUICE

As our reliance on electric and electronic systems increases, many businesses—and consumers—need better performance than the 99.9 percent reliability the local electric power grid provides. These demanding users need what utilities call "premium power": pure, top-grade electrical juice that flows without fail. Manufacturers, banks, telecommunications providers—just about any company that depends on computers or digital equipment such as Web servers and routers—need premium power. And the only sure way to get it, energy experts agree, is to generate it yourself.

Industrial operations have long done just that, but residential or commercial users couldn't fulfill their needs using the available small power systems: the diesel generators that keep hospitals alive are too loud and dirty for a suburban neighborhood. Solar power keeps getting cheaper, but it can't always deliver the kilowatts. Not that these technologies were capable of making much difference, since state laws kept most power consumers shackled to their local utility. Deregulation is changing all that, freeing consumers and unleashing a torrent of investment and innovation. The first products of this wave of technology development are clean, quiet and dependable microturbines, developed in the 1960s to provide electric power for air conditioning and circulation systems on aircraft. They descended toward the consumer market in the early 1990s thanks to Rosen Motors, the company created by Compaq Computer cofounder Ben Rosen to build turbine-powered hybrid electric cars.

> Any organization that depends on computers and other digital equipment needs to have pure, top-grade electrical juice that flows without fail. And the only sure way to get this "premium power" is to generate it yourself.

Rosen's company was ahead of its time, though, and it paid the price, folding in 1997 just before Toyota and Honda rolled out gas-electric hybrids in Japan. Last year, the Japanese auto giants brought hybrids to America, forcing Detroit to lay hasty plans for its own hybrid cars.

Although the company's automobile venture collapsed, its microturbine power source lives on in another Rosen venture: Chatsworth, CA-based Capstone Turbine. Capstone's 30-kilowatt microturbine functions just like the several hundred-megawatt natural-gas-fired power plants that prop up the electrical grid. Ignite the fuel (natural gas, gasoline, kerosene—just about anything that burns) and rapidly expanding combustion gases push the turbine blades to spin a rotor and generate electricity. Exhaust from the microturbines contains only about three parts per million of smog-forming nitrogen oxides—about a hundred times less than diesel generators—and virtually no soot.

And the microturbine is ready to go the distance without burning out, thanks to air bearings that float the turbine on a turbulent film of air just two micrometers thick. The air bearings experience no friction and no wear, even at punishing speeds—more than 1,500 revolutions per second in the Capstone turbine—that would burn up lubricated bearings.

Fuel-cell power plants will run even smoother and cheaper because they are solid state: rather than burning hydrocarbons, fuel cells employ steam and catalysts to release the fuel's hydrogen atoms and strip away its electrons *(see "Fuel Cell Fundamentals," p. 76)*. Eschewing combustion and bypassing mechanics makes this technology clean and efficient: fuel cells running on natural gas release virtually no nitrogen oxide and convert 40 percent of the fuel's energy into electricity (a third more than the microturbine). Capturing the wasted energy by using the fuel cell's hot water by-product to warm a building's air and water pushes the overall energy efficiency to 80 percent or more.

At least half a dozen types of fuel cells are under development for electrical power generation. The best hope for smaller, more affordable units lies in a light, compact version based on a structure known as a proton exchange membrane. This is a technology for which we can thank the auto industry; Ford, DaimlerChrysler and Toyota are investing billions to make this variety of fuel cell powerful and cheap enough to replace the internal combustion engine *(see "Fill'er Up with Hydrogen,"* TR *November/ December 2000).*

As the technology spreads from the auto industry, a host of startups, includ-

Micropower Movers

COMPANY	STRATEGY
Ballard Power Systems (Burnaby, British Columbia)	Developing fuel cells for portable generators, stationary power plants and electric cars. Look for Ballard's portable generators sold by Coleman Powermate this year, and for Ballard's fuel-cell power plants and engines by 2004.
Capstone Turbine (Chatsworth, CA)	Makes microturbines for stationary power plants and hybrid electric trucks and buses. Capstone has sold more than 1,000 of its 30-kilowatt turbines in the past two years and recently added a 60-kilowatt unit.
Encorp (Windsor, CO)	Makes microelectronic switches that keep micropower devices in sync with the grid and communications interfaces that provide remote control. Utilities are using Encorp's equipment to create "virtual power plants."
General Electric (Fairfield, CT)	Microturbines: GE is acquiring Honeywell, and says it considers microturbines a "core technology." Fuel cells: GE is working with Plug Power to develop residential fuel-cell generators.
Honeywell Power Systems (Albuquerque, NM)	Aerospace contractor transformed its jet-engine and turbocharger technologies into a 75-kilowatt microturbine aimed at restaurants, hotels and other commercial establishments. Now working on a 350-kilowatt microturbine for larger operations.
Plug Power (Latham, NY)	Partnering with General Electric to develop residential fuel cells, with commercialization targeted for the first half of 2002.

ing Ballard Power Systems of Burnaby, British Columbia, and Plug Power of Latham, NY, are pushing proton exchange membrane technology for stationary power production. The goal is 1- to 15-kilowatt power plants to enable a family to declare independence from the electrical grid; larger units, 60 to 250 kilowatts, would do the same for offices. Though these companies have aggressive marketing plans, reality—in the form of engineering obstacles—has begun to intrude. Plug Power and its marketing partner, General Electric, planned to be the first to market with thousands of residential units this year. Engineering the units for continuous, glitch-free operation is proving to be unexpectedly complex, however, and Plug Power now expects to introduce commercial fuel-cell systems in the first half of 2002.

AN ELECTRICAL SAFETY NET

Micropower is finding some of its first applications in remote operations that have inadequate access to centrally generated electricity. Microturbines have been a hit on oil-drilling rigs in Alberta, Colorado and Texas, for example. These rigs sit above reserves of energy-rich liquid gold, but lie either beyond the grid or at its edge, where the trickle of electricity can't support heavy equipment. Modern-day wildcatters are also under pressure from environmental regulators to curb the flaring of the sulfur-laden gases associated with many wells. Microturbines will run on just about anything, including this "sour gas," so haul one to the well head and you can put this environmental nuisance to work powering the pumps.

The economics of generating power without incurring a fuel cost is so compelling that microturbines may turn many oil wells into remote power plants that generate surplus power for sale over the grid. The capacity for expansion is enormous: oil wells in Texas alone typically flare a billion cubic meters of sour gas a year. That's enough to generate more than 400 megawatts of electricity, equivalent to a mid-sized utility power plant. Landfills and wastewater treatment plants may be the next to cash in. Since last spring, a Capstone microturbine has been digesting the methane that ferments forth from the world's second largest trash pile—Los Angeles County's Puente

Making microturbines: A Capstone technician checks a unit's quality (above); parts of the turbine await assembly (below). Capstone wants to make 100,000 turbines a year.

Hills landfill—while generating only 1.3 parts per million of nitrogen oxides. That's a lot cleaner than the 30 parts per million released when the gas is flared.

But transforming waste gas is a niche opportunity, and companies like Capstone and Ballard are hoping for much more. Their plan: catch the deregulation wave and transform millions of power consumers into power producers. Deregulation is sweeping away the monopoly protections that kept new power producers—particularly residential and commercial consumers—out of the market. "Under the monopoly environment it didn't matter if you had these wonderful technologies to self-generate because you were obligated to buy your power from the utility," says Wayne Gardner, manager of business development and strategy at Exelon Capital Partners—the Philadelphia-based venture capital arm of U.S. power giant Exelon.

As deregulation offers consumers greater freedom to generate power, it also gives them more reason to do so. The rocky transition to a deregulated market is casting a haze of uncertainty over the power industry, discouraging utilities from adding generating capacity and upgrading their transmission lines. Energy experts blame California's hesitating transition toward a competitive power market for its meltdown this winter. And one solution to an ailing grid, it is becoming clear, is micropower. "Premium power is clearly the dominant near-term market for distributed power," says Dan Rastler, a distributed power expert with the Electric Power Research Institute in Palo Alto, CA. "The existing distribution system is not capable of meeting the reliability needs of that market."

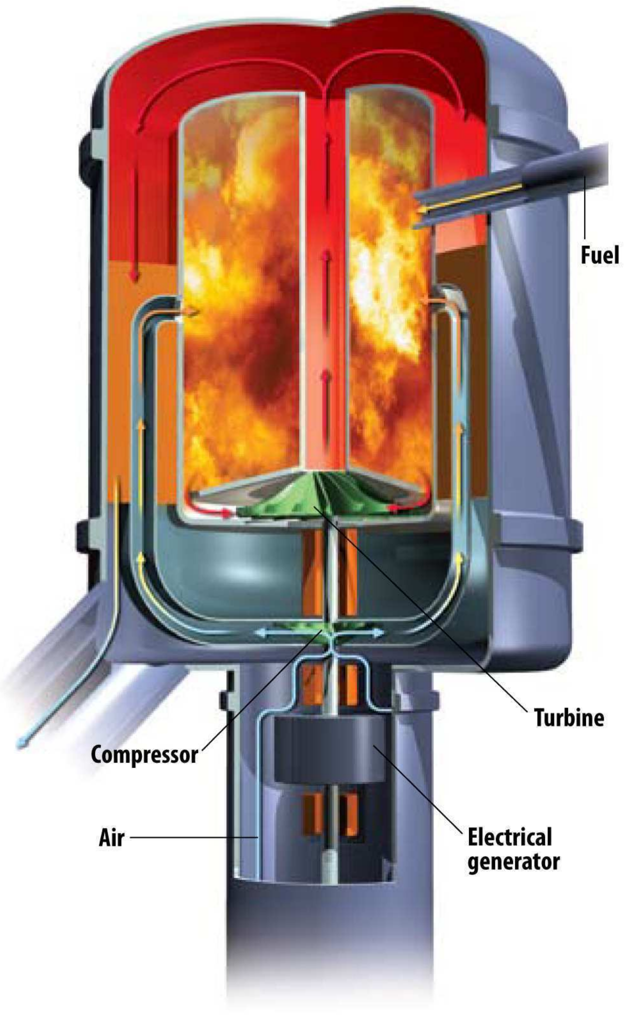
Premium power is already a \$7 to \$10 billion-per-year market in North America, according to the research firm Frost & Sullivan. Today, most of that comes from batteries and diesel engines serving as backup power sources. But the freedom to generate one's own electricity could blow this market open. Seekers of premium power who hook up microturbines and fuel cells to the natural-gas line are no longer limited to using their generators only when the lights go out. They can save money by powering up whenever the grid price exceeds the cost of fuel. Some states even permit micropower producers to sell surplus power back to the grid for a profit.

This ability to play the power markets will grow as utilities move toward real-time pricing, where the price of power from the grid reflects the cost to produce it. During times of peak demand, when utilities must fire up their least efficient plants, prices spike. Micropower units will monitor pricing through an Internet connection or via a digital signal embedded in the electricity itself. Using this information, they will compare quotes for gas and electricity and automatically turn themselves on when the spread is favorable.

Yet power generation is not a core competency for most businesses (let alone residential consumers), so it will be important to find the folks who can run micropower smoothly. With natural-gas prices rising, switching on micropower at the wrong time could cost a bundle. "The technology developers and a lot of the investors have placed more focus on getting the technology developed without thinking on the operations side of who's going to support it, who's going to install it, who's going to warranty it," says Exelon's Gardner.

Capstone's best answer is Williams International, a Tulsa, OK-based energy giant that sold or leased 60 of the first 1,000 microturbines that Capstone produced through last November. Williams, whose pipelines carry nearly 20 percent of the U.S. natural-gas supply, provides a complete energy service package: financing the micropower unit, providing power from the grid, and helping consumers determine when peak shaving makes sense (the company is a leading trader of electricity and natural gas). Mory Houshmand, director of the Williams Distributed Power Services unit, says Williams expects its wholesalers in the United States, South America and southeast Asia to install about 1,500 microturbines this

Inside a Microturbine

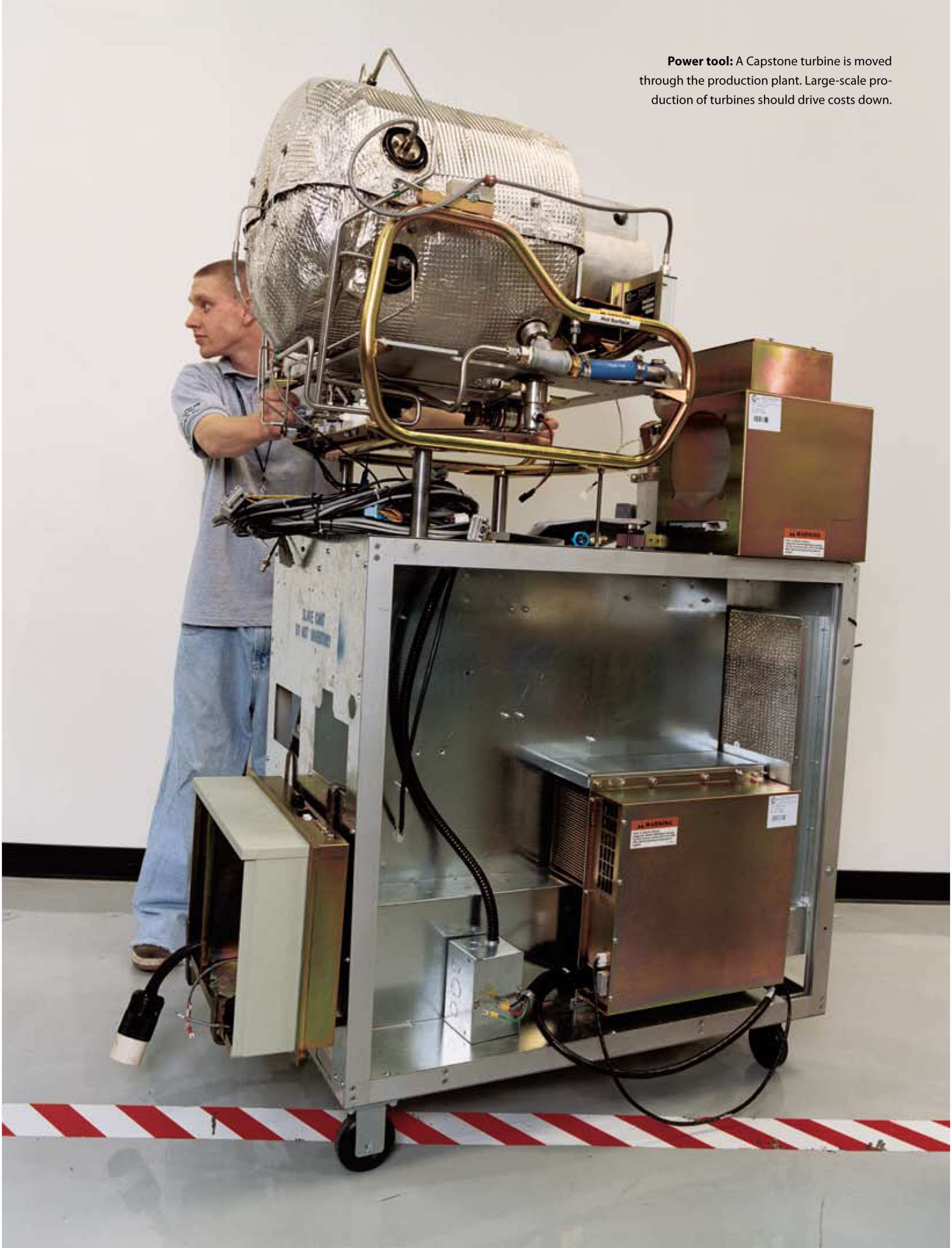


Fuel enters the combustion chamber. The turbine can run on natural gas, gasoline, kerosene—virtually anything that burns.

The hot combustion gases spin a turbine, which is connected to the shaft of an electrical generator. The exhaust transfers heat to incoming air.

Air passes through a compressor and is warmed by the exhaust gases before entering the combustion chamber.

SLIM FILMS



Power tool: A Capstone turbine is moved through the production plant. Large-scale production of turbines should drive costs down.

year, and another 2,000 to 3,000 in 2002.

Enron—a Houston-based energy giant and rival of Williams—sees the same opportunity coming with fuel cells. Last fall, Enron forged an alliance with FuelCell Energy, investing $5 million in the Danbury, CT, startup and gaining options on another 1.3 million shares of stock if the company sells more than 55 megawatts' worth of its molten-carbonate fuel cells (enough to light up 10,000 homes). Jeremy Blachman, chief operating officer for Enron Energy Services, is bullish on micropower. "When the market price of power pops all over the place and gets to some of the levels that we've seen during peak summer demand—up to $7,000 per megawatt-hour—then distributed generation with fuel cells becomes much more economic." (Even at today's sky-high prices, natural gas would cost less than $100 per megawatt-hour to fire up a microturbine and less than $75 per megawatt-hour to run a fuel cell.)

POWER FROM EVERYBODY

For the big energy companies like Williams and Enron, the lure of micropower goes beyond the selling and leasing of small generating plants. These organizations see an opportunity developing that will enable them to sell gas and electricity en masse. Aggregate the output of thousands of fuel cells and small turbines into a "virtual power plant," and peak shaving becomes power trading. If Williams could remotely activate thousands of microturbines on its customers' premises, the company could generate hundreds of megawatts for sale on the wholesale market. Houshmand says this could dramatically lower the cost of the microturbine, enticing companies like his own to bear a larger share: "Look at cell phones. A few years ago they were very expensive, and now service providers are giving them away. Why? Because they're selling the service."

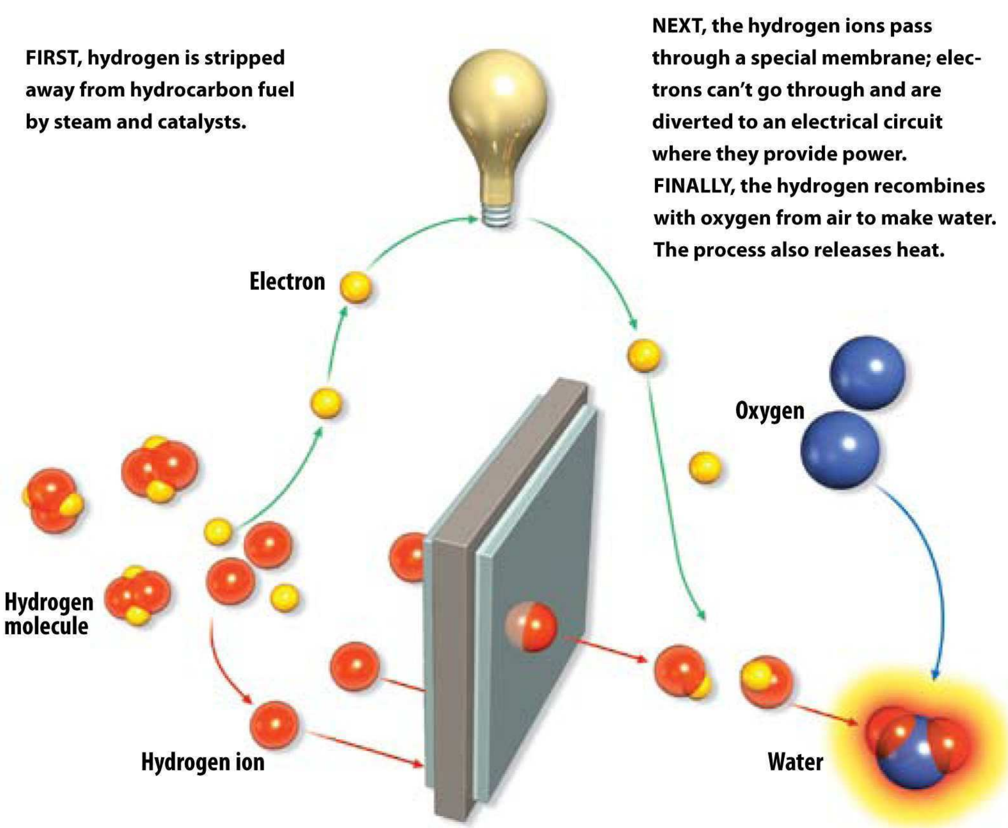
The notion of virtual power plants could charm traditional utilities that, until now, have been lukewarm toward technologies that let consumers and businesses generate their own power.

The notion of virtual power plants could also charm traditional utilities that, until now, have been lukewarm toward technologies that let consumers and businesses generate their own power. In the past, utilities erected barriers to distributed power, such as maintenance fees for emergency backup service. Ritchie Priddy, associate director for distributed energy at Cambridge Energy Research Associates in Cambridge, MA, says that utilities remain ambivalent about micropower. For example, many utilities now pay retail for surplus energy from solar panels or wind turbines—a trickle of energy that poses little competition. But the same utilities pay little or nothing for surplus power from microturbines and diesels, where the kilowatts could really add up. "Some utilities are embracing distributed generation, but quite frankly they do it on their terms," says Priddy, a former utility company manager.

Micropower advocates like Priddy want to convince power companies that the proliferation of micropower generators could aid their operations by helping to stabilize the grid. There are some hopeful signs. Japanese utilities, for example, are subsidizing the development of residential fuel cells that heat water and churn out one kilowatt of electricity—nowhere near enough juice to power the household (a toaster alone consumes more than a kilowatt), but enough in aggregate to ease the strain on overloaded power lines. Virtual power plants could have a more dynamic effect on the grid: rather than asking consumers to turn off their equipment when power demand crests, imagine California's beleaguered grid controllers remotely activating thousands of microturbines and fuel cells to meet peak demand.

The communications equipment and power electronics to safely operate micropower units remotely is already here, and energy service firms have begun to test this virtual backup model using diesel generators

Fuel Cell Fundamentals



SLIM FILMS

(see "The Virtual Power Plant," this page). Their window of opportunity may be closing, however, as environmental regulators crack down on diesel pollution. Still, micropower enthusiasts hope these early experiments will clear the way for cleaner micropower technologies. "If fuel cells and microturbines come on heavy, the opportunity explodes," says Bill Saylor, chief technology officer at Encorp—a remote power control company in Windsor, CO, that is assembling one of the first virtual power plants.

The final element that will make micropower a killer app is scale. Gas-fired power plants have been shrinking since the early 1980s, when smaller factory-produced turbines began to replace the giant ones built on site; micropower could push that trend to the extreme. Capstone's 30-kilowatt unit now sells for about $27,000, but the company figures that if it can gear up for a manufacturing volume of 100,000 units per year, price could drop to $12,000. That works out to $400 per kilowatt of generating capacity, which is about what you would expect from gas-fired power plants 10,000 times larger.

Fuel cells are a newer technology and have a longer way to go to reach economic parity: the first fuel cells will cost $2,500 to $5,000 per kilowatt. But the fuel cell industry has an ace up its sleeve: carmakers are expected to begin cranking out fuel-cell cars by the thousands in 2003 or 2004. With the efficiencies that should accompany this mass-production, the cost of electricity from fuel cells should ultimately plummet to $100 to $300 per kilowatt.

At that point, micropower would begin to seize its most revolutionary opportunity: delivering electricity to the 1.8 billion people in the world who now have no access to centrally generated electricity. Ironically, many of the electrically deprived live in countries blessed with vast energy resources but lacking the capital needed to build a grid and distribute energy to their people. South African archbishop Desmond Tutu once noted that "one of the obscenities of Southern Africa is to see electric power lines strung across a rural landscape overshadowing communities where women spend most of their days walking kilometers to find firewood just to survive."

Micropower could end that disparity. In fact, one wholesaler Williams International is counting on to meet its ambitious microturbine sales targets is already installing its first units in China. The first application will be to provide premium power for an information technology-oriented industrial park in the southeastern city of Nansha. But Williams's Mory Houshmand is confident that microturbines will filter out into the Chinese countryside, where extending the grid is costly and replacement parts for diesel generators rare. The microturbine will burn whatever fuel can be found. And with a little investment, China could find a bunch for free: only U.S. landfills release more methane than China's; and for coal mine gases, China is second to none.

Combining waste products with high technology to make electrical power: California, are you listening? ◊

The Virtual Power Plant

Flicking on a light switch in Denver or Albuquerque may soon mean tapping power from a network of small electrical generators distributed throughout the region. These are two of the first "virtual power plants"—and you're likely to see a lot more, thanks to the growing popularity of micropower generators such as microturbines and fuel cells.

In the future, such virtual power plants might link hundreds or thousands of generators and rival the 250- to 1,000-megawatt power streams that big utility plants churn out. For now, though, they're starting small. Denver, for example, plans to link five large backup generators at commercial and industrial facilities. Together, these generators can dispatch a steady five megawatts of power. The Denver system is a joint project of Encorp—a Windsor, CO-based producer of remote-controlled power-switching gear—and Celerity Energy, an energy services firm in Portland, OR. In Albuquerque, Celerity is working with micropower networking firm Sixth Dimension of Fort Collins, CO, on a virtual plant comprising about a dozen internetworked backup generators. Total possible yield: 25 megawatts.

Here's how it works. The utilities pay the virtual-power-plant operators up front for the cost of bundling and maintaining the capacity, which usually sits idle. When power is actually fed into the grid from the network of small generators, the utility covers the fuel costs. And it's not just about backing up the grid: independent power producers can use virtual power plants to play the wholesale markets, cashing in during extreme hot or cold weather when power demand spikes and desperate utilities send prices through the roof.

There is one hitch. Right now, most of the distributed power production comes from diesel-fired generators, which foul the air with soot and with smog-producing nitrogen oxides. Bill Saylor, Encorp's chief technology officer, says the diesels in their virtual plants will be converted to burn mostly natural gas. This transition, he says, will cut nitrogen oxides to below 300 parts per million. But even that level may be too high for environmental regulators concerned with urban air quality. Texas, for example, intends to limit small generators to nine parts per million of nitrogen oxides—the level at which clean-burning gas-fired power plants pump them out. And beginning in 2005, Texas regulators plan to further squeeze the small generators, limiting them to just three parts per million.

Such strict emission constraints worry some advocates of distributed power. But Ake Almgren, CEO of leading microturbine maker Capstone Turbine, welcomes the Texas standard. "There's no reason why distributed generation should be accepted unless it's as clean or cleaner than state-of-the-art large-scale generation," he says. Capstone's microturbines already emit nitrogen oxides at concentrations of about three parts per million, and Capstone is experimenting with catalytic combustion to run even cleaner: "We believe we can come down to as close to zero as is meaningful to measure."

Zero pollution sounds fanciful. But if that's the target, fuel cells could get there before turbines do. Fuel cells use catalysts to eliminate combustion altogether, reducing nitrogen oxides to less than one part per million. That kind of performance would make virtual power plants virtually nonpolluters.

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The Programmable Pill

"SMART" METHODS OF DELIVERING DRUGS TO THE BODY—BASED ON MICRO- AND NANOTECHNOLOGY—COULD REDUCE SIDE EFFECTS, MAKE BETTER USE OF EXISTING DRUGS AND OPEN THE DOOR TO ENTIRE CLASSES OF NEW TREATMENTS.

BY ALEXANDRA STIKEMAN

ILLUSTRATION BY JANA LEON

THE PATIENT LEANS BACK IN HIS CHAIR AND CLOSES his eyes, waiting to receive his first chemotherapy treatment for advanced colon cancer. His nurse locates the tiny catheter just beneath the skin of his chest and connects it to an IV tube. A clear fluid containing an anticancer drug travels down the tube, through the catheter and into the man's blood vessels. The drug travels throughout his body in search of the fast-dividing cells characteristic of cancer—but only a relatively small portion of the drug will reach those cells. Instead, much of it will end up attacking hair follicles, immune system cells and tissues where noncancerous cells are dividing quickly. The treatment lasts an hour as the patient sits there, apprehensive not only about his disease but about side effects. Will he lose his hair? Will he feel nauseous? A few hours later, nausea sets in. By the next treatment, the hair loss he feared has begun.

Now fast-forward 10 years or so. Gone are the catheter and the shotgun approach. In their place is a remarkable little particle, invisible to the naked eye, that contains far more intelligence than the entire current system of drug delivery. Taken orally, the particle passes undisturbed through the stomach and small intestine and into the colon, where it homes in directly on the tumor cells. There, it releases a powerful anticancer drug that destroys just the cancerous cells—with no side effects.

Sound far-fetched? Well, it isn't possible yet. But it could be quite soon, thanks to a new generation of "smart" delivery vehicles under development at a handful of universities and startup companies. These new methods offer the ability to precisely control the timing of a drug's release. What's more, they aim for laserlike targeting of just the right tissues and cells. And a little farther in the future lies the capacity to operate autonomously, gathering feedback from the body and adjusting treatment accordingly. The pioneers in this young field believe they will bring the first of these new weapons against disease into clinical trials as soon as five years from now, freeing patients from the pain and side effects of pills and injections, and also opening the door to whole new classes of treatments that aren't possible with today's delivery systems.

Gathering Speed

Smart drug delivery is still in its infancy—and at the same time it's a discipline whose time has come. At the moment, most of the research is happening in academic labs, along with a few start-ups (mostly spun out of academe). But the promise of the technology is so great that it has caught the attention of large drug companies and other manufacturers. "They're certainly poking around at conferences," says Carl Grove, president of Columbus, OH, startup iMedd. "Even the Motorolas and the Intels, you see them nosing around too." And though analysts have yet to offer their forecasts for the field, insiders often cite a 1998 report from the European Network of Excellence in Multi-functional Microsystems (an industry consortium funded by the European Union) predicting a worldwide market of $1 billion for microfabricated drug-delivery devices by 2002.

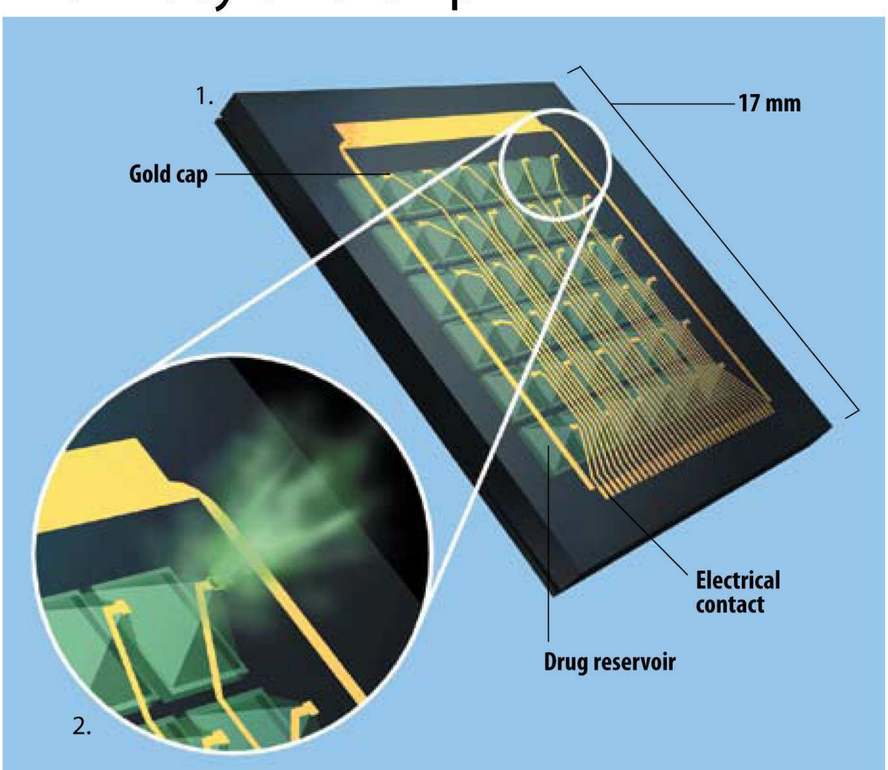
Much of this interest is driven by rapid progress in microfabrication. Researchers now have the ability to build devices with features small enough to interact with single cells, and even individual molecules. Getting the devices small enough is the key to their promise, says Mauro Ferrari, director of the Center for Biomedical Engineering at Ohio State University. "There are some major unsolved problems in medicine that can only be solved with micro- and nanotechnologies."

When the delivery systems reach practicality, there's a whole new suite of potential drugs waiting in the wings: proteins discovered as a result of the recent explosion of genomic information. But expanding the use of proteins as drugs demands much better means of delivery than are currently available, since most of these large biological molecules are either too potent to deliver through injection, or too fragile to withstand the enzymes and drastic changes in pH found in the stomach and intestines. With an entire new class of protein drugs in view, the enabling technologies in hand, and corporate interest growing, the next couple of years look like just the time for smart drug delivery to emerge as a field.

Perfect Timing

If this field is now poised for takeoff, it's partly as the result of work going back a couple of decades. In the 1970s, MIT biomedical engineer Robert Langer worked out ways to build pills out of special polymers that dissolved at predictable rates to control drug dosages. Then, in 1993, Langer's thinking on drug delivery leaped into the Information Age. "I was watching this TV show, and they were showing how computer chips are made, and I thought, boy, this would be a really neat way of making a drug-delivery system." Langer buttonholed MIT material scientist Michael Cima and they set to work.

Pharmacy on a Chip



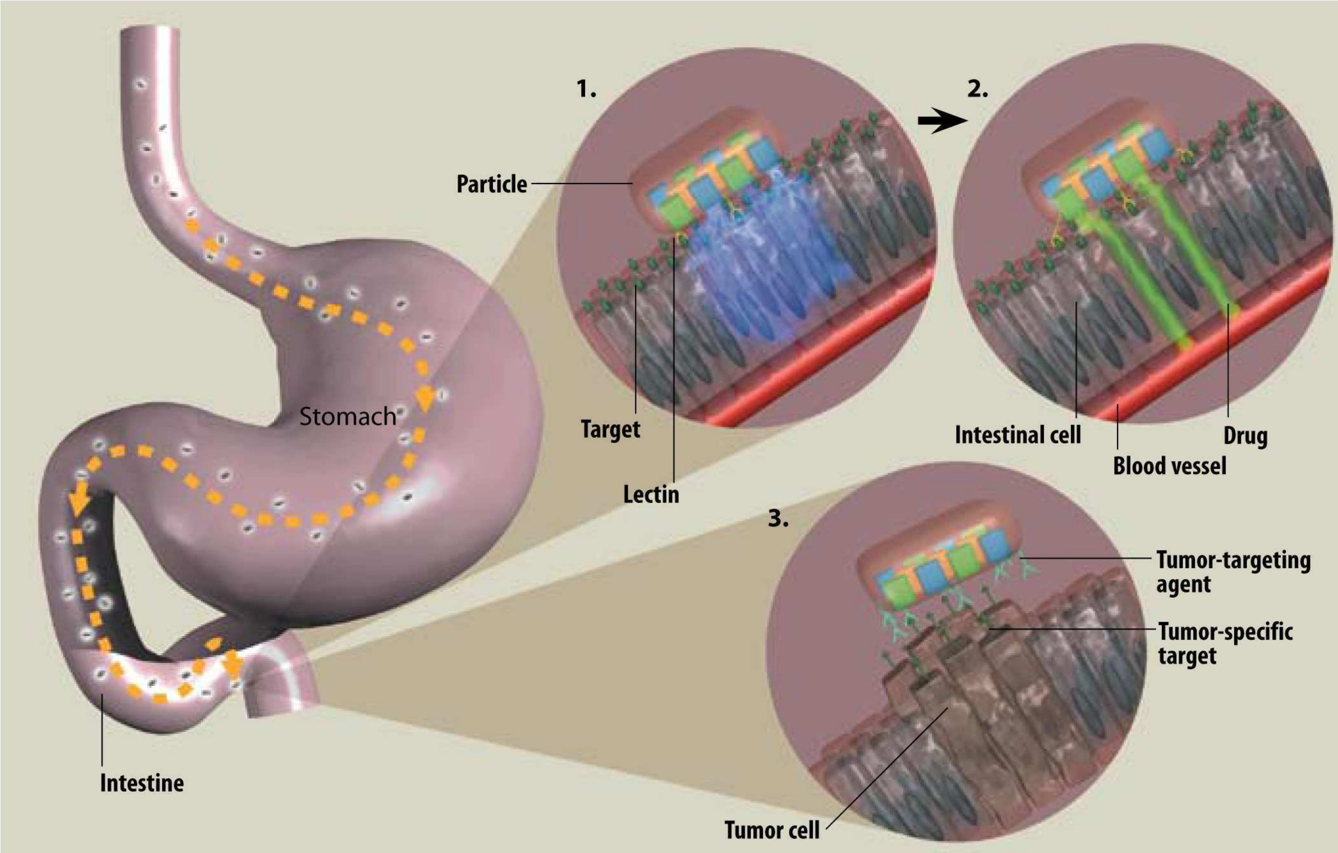
MicroCHIPS' implantable silicon chip could hold years' worth of drugs in tiny reservoirs; one reservoir is being filled below.

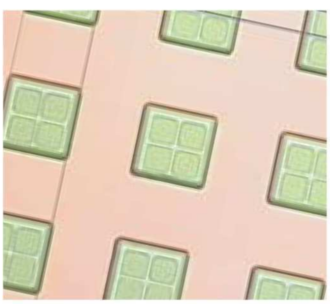
1. A gold cap atop each reservoir would hold the drug in; each cap would be attached to its own electrical contact.

2. Applying a voltage to a cap would cause it to dissolve, releasing the reservoir's store of drug. An implantable battery and microprocessor could power the chip and control when each reservoir opened.

ILLUSTRATION: JOHN MACNEILL; SOURCE: MICROCHIPS; PHOTOGRAPH: FURNALD/GRAY

A Fleet of Medicine Machines





Tejal Desai's chiclet-shaped silicon particles (green, at left), once swallowed, could carry a cargo of drugs safely through the harsh environment of the stomach. To deliver those drugs to the bloodstream, Desai's team might coat one side of each particle with a protein called lectin that binds to a target found only on intestinal cells.

1. When a particle bound to those cells, it would first release chemicals to open up the spaces between the cells and to fend off enzymes that might degrade the drug.

2. When the coast was clear, the particle would release the drug, which could pass safely through the intestinal wall and into the nearest blood vessel.

3. To target intestinal or colon cancer, the team might coat particles with molecules that bound only to tumor cells. That way, the toxic drugs would affect only diseased tissue.

ILLUSTRATION: JOHN MACNEILL; SOURCE: TEJAL DESAI, UNIVERSITY OF ILLINOIS AT CHICAGO; PHOTOGRAPH: TEJAL DESAI

Their goal was to create an implantable microchip that could hold several years' worth of medications, a miniature pharmacy that would dispense each dose automatically on schedule, freeing patients from complicated regimens. Five years later, Cima's lab came up with a dime-sized silicon chip containing 34 drug reservoirs, each covered by a thin gold cap. Applying a small voltage to a given cap causes it to dissolve and release the reservoir's contents *(see "Pharmacy on a Chip," p. 80).*

The beauty of the device lies in its capacity to deliver drugs in a way that closely mimics how the body naturally produces chemicals—some in a steady stream, others in pulses. By carefully timing the voltage applied to each reservoir, the researchers could create different patterns of drug release. The chip could also hold many different kinds of drugs—a system that, conceptually, would work well for AIDS patients who must take 12 to 40 pills a day, at very specific intervals.

Last year, Cima and his colleagues successfully tested their system in animals. They implanted the chip in the back of a rabbit's eye to simulate a treatment replacing the frequent eye injections required to combat vision loss from diabetes or macular degeneration. In the rabbit study, the researchers found that not only were they able to control the release of the drug, but the device itself didn't cause any significant inflammation to the surrounding tissue.

Although this miniature pharmacy is promising, it still isn't ready to run independently. The voltage on each reservoir must be controlled by an external power source connected to the chip via wires threaded through the animal's tissue. Eventually, Cima hopes to make the entire system implantable by adding a tiny battery and a preprogrammed microprocessor. This will be the easiest part of the project, says Cima, who hopes to have a completely self-contained device ready for testing by the end of this year.

While the device is still under development, one of Langer and Cima's former graduate students, John Santini, is gearing up to bring it to market. Encouraged by early lab

successes, Santini founded Cambridge, MA-based MicroCHIPS in February 1999. The company has made its own improvements in the chip's design, including squeezing up to 100 drug reservoirs onto some versions. Since each reservoir can hold only minute amounts of either powder or fluid, the company is focusing on using the chips for delivering potent drugs such as pain medications, anticancer agents, hormones and steroids. MicroCHIPS has also signed a deal with an undisclosed pharmaceutical company to develop chips carrying its proprietary drug; Santini hopes to have those chips ready for human trials in four to five years.

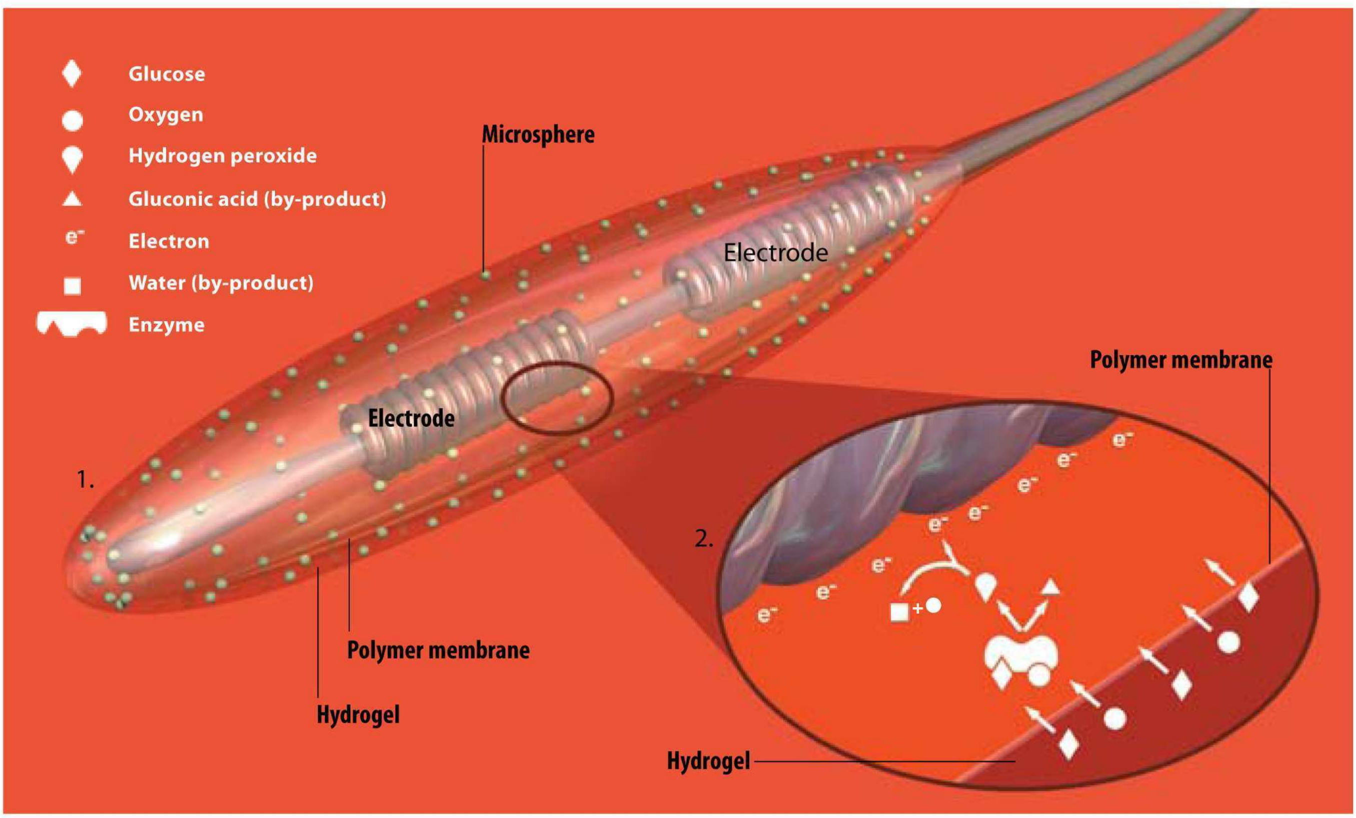
"People are finally starting to believe that microchip technology can be applied to drug delivery," enthuses Santini. "Now we can take this technology and go in 50 different directions." One possible direction: completely biodegradable polymer chips. Or a radio-controlled chip that would allow a doctor to reprogram the device remotely after implantation, should the patient need a new dosing schedule.

On Target

If the device that Cima has built specializes in complex scheduling, other groups are focusing on precise targeting. Take Ohio's iMedd, one of the first companies in the field. IMedd was founded in Silicon Valley to commercialize the inventions of Ohio State's Ferrari (then a professor at the University of California, Berkeley). When Ferrari went to Ohio in 1998, the company followed; but it continues to collaborate with former graduate students from Ferrari's Berkeley lab.

One of them is Tejal Desai, now an assistant professor of bioengineering at the University of Illinois at Chicago. She and iMedd are building chiclet-shaped silicon particles so small (150 microns across and 50 microns thick) they're invisible to the naked eye. On one side, the researchers etch from two to 20 drug-containing reservoirs, each sealed with a polymer plug. Like pills, the particles are swallowed, but unlike pills, they release drugs only at a predetermined time and location. "We want to make something that actually responds to the environment and interacts with the cells, instead of just going in and releasing a drug," says Desai.

Sensible Sensors



1. Francis Moussy's implantable glucose sensor could measure diabetics' blood glucose continuously for years at a time. To prevent scar tissue from forming around the sensor, Moussy would coat it with a gel-like polymer, or "hydrogel," containing hollow "microspheres." The spheres would gradually dissolve and release anti-inflammatory drugs to prevent scar-causing immune reactions, as well as factors to encourage blood vessels to grow near the sensor, giving it access to glucose in the blood.

2. Glucose and oxygen from the blood would pass through the hydrogel and a semi-permeable polymer membrane that lay underneath it. Inside the sensor, an enzyme would cause glucose and oxygen to react, forming hydrogen peroxide. When hydrogen peroxide reached the sensor's core, a voltage applied to the electrode would cause it to release electrons. Electrons accumulating on the electrode's surface would produce a current proportional to the amount of glucose in the blood.

ILLUSTRATION: JOHN MACNEILL; SOURCE: FRANCIS MOUSSY, UNIVERSITY OF CONNECTICUT HEALTH CENTER; PHOTOGRAPH: FRANCIS MOUSSY

The targeting mechanism is a special coating deposited over the reservoir-bearing side. In initial experiments, Desai's team is making particles aimed at delivering fragile drugs such as proteins directly to the bloodstream, so the researchers are coating the particles with a tomato protein called lectin that binds specifically to cells lining the intestine. The idea is that the particles could travel undisturbed through the harsh environment of the stomach, protected by the silicon casing. Once a particle reached the intestine, the lectin-coated side would bind to the lining. There, the system would ferry the drug quickly across the intestinal lining into the nearest blood vessel.

To get the job done, some of the reservoirs would hold chemicals to widen the spaces between the intestinal lining cells, and some would carry another chemical that blocks the enzymes that could degrade the drug. By modifying the polymer plugs covering the reservoirs, the researchers could make sure that the protective chemicals were released first. With these lines of defense in place, the drug could pass safely through the intestinal wall and into the bloodstream, and the empty particles could pass through the rest of the digestive tract.

Currently, Desai is testing the basic setup in rats. If that works out, she'll begin adapting the particles for an array of targets. One idea is to replace the surface layer of lectin with an antibody that binds to tumor cells in the colon; that way, the particle could carry anticancer drugs directly to cancerous masses *(see "A Fleet of Medicine Machines," p. 81)*. Such a system could virtually eliminate side effects, revolutionizing treatment for the 130,000 or so patients who are diagnosed with colon and rectal cancer each year in the United States.

While Desai's system offers great flexibility, in some cases intravenous delivery is still best. IMedd is therefore developing a polymer particle small enough for injection—just a few microns across—that will have the same targeting abilities as Desai's prototype. "Now it gets even more complicated," says Ferrari. "You need to make a delivery device that can perform multiple functions even at that size." Derek Hansford, a biomedical engineer at Ohio State, is leading a project that aims to deliver just that. "The biggest challenge currently is in producing uniform particles with uniform material properties in large quantities," says Hansford. Eventually, he plans to fill the particles with drugs and coat them with targeting agents in a system much like Desai's.

Closing the Loop

A microscopic device stocked with drugs and a keen aim would be clever indeed, but the ultimate intelligent drug-delivery apparatus would also boast one more piece of equipment: a biosensor, which would enable it to respond to changes in the body's chemistry and behavior. Coupled with a drug-delivery device, a biosensor could sense when concentrations of a drug were too high or too low, for example, and tell the device to respond accordingly—making the entire system not just smart but also autonomous.

Although almost all researchers in the field of smart drug delivery have an eye on biosensors, sometimes key advances come from outside the field—for example, from someone working directly on the sensors themselves. Take University of Michigan electrical engineer Kensall Wise, who is developing a tiny implantable neural probe, designed to measure electrical activity in the brains of patients with diseases like epilepsy or Parkinson's disease. Wise quickly realized such a device could do double duty, delivering drugs to combat the very diseases it was monitoring, right where they were needed most.

WHEN SMART DEVICES BECOME REALITY, A WHOLE NEW SUITE OF POTENTIAL DRUGS WILL BE WAITING IN THE WINGS—PROTEINS DISCOVERED AS A RESULT OF THE EXPLOSION IN GENOMIC INFORMATION.

An area where biosensors might have an even greater impact than they would in brain diseases is diabetes. Approximately 16 million people in the United States suffer from diabetes, making it the country's seventh leading cause of death and one of its most costly chronic illnesses. Studies have shown that patients who diligently control their blood glucose levels can prevent or delay the secondary complications of diabetes—kidney and eye disease, for example—by up to 60 percent.

Finger-prick blood tests can tell patients what their sugar levels are at specific moments during the day, but they don't say anything about the fluctuations between tests. Patients risk taking too much or too little insulin, both of which can cause serious and even life-threatening side effects. A glucose sensor implanted directly in the body and connected to an insulin-delivery device could solve those problems.

But nobody has come up with a glucose sensor that can survive an extended tour of duty, because the body's response—scar formation—prevents delicate biosensors from making accurate readings. "The sensors are really the rate-limiting step in this whole thing," says Texas A&M University engineer Michael Pishko. "Once we've got the sensor down, which is probably still five years away, fixing it to an insulin-delivery device will happen very quickly."

Francis Moussy, a biomedical engineer at the University of Connecticut Health Center, believes he's already found a solution. Moussy is developing a sensor smaller than a grain of rice that uses an enzymatic reaction to measure blood glucose levels. To evade scar tissue, Moussy plans to cover the sensor with tiny "microspheres," beads made of a biodegradable polymer that he can fill with different chemicals. In the body, the microspheres would slowly degrade, releasing anti-inflammatory agents that block scar formation. Other microspheres would release a chemical to promote the growth of blood vessels near the sensor's surface, giving the device greater access to glucose in the blood *(see "Sensible Sensors," p. 82)*.

Confident that his system will work based on preliminary tests, Moussy is working on a design suitable for mass production. And since many smart drug-delivery devices are being designed to take advantage of manufacturing techniques already proven in the computer industry, there's reason to think that scaling up production of the devices could go smoothly when the time comes. That time may be as little as a decade away. And it could mark the beginning of an era in medicine that is not only "smarter" but a whole lot more humane. ◊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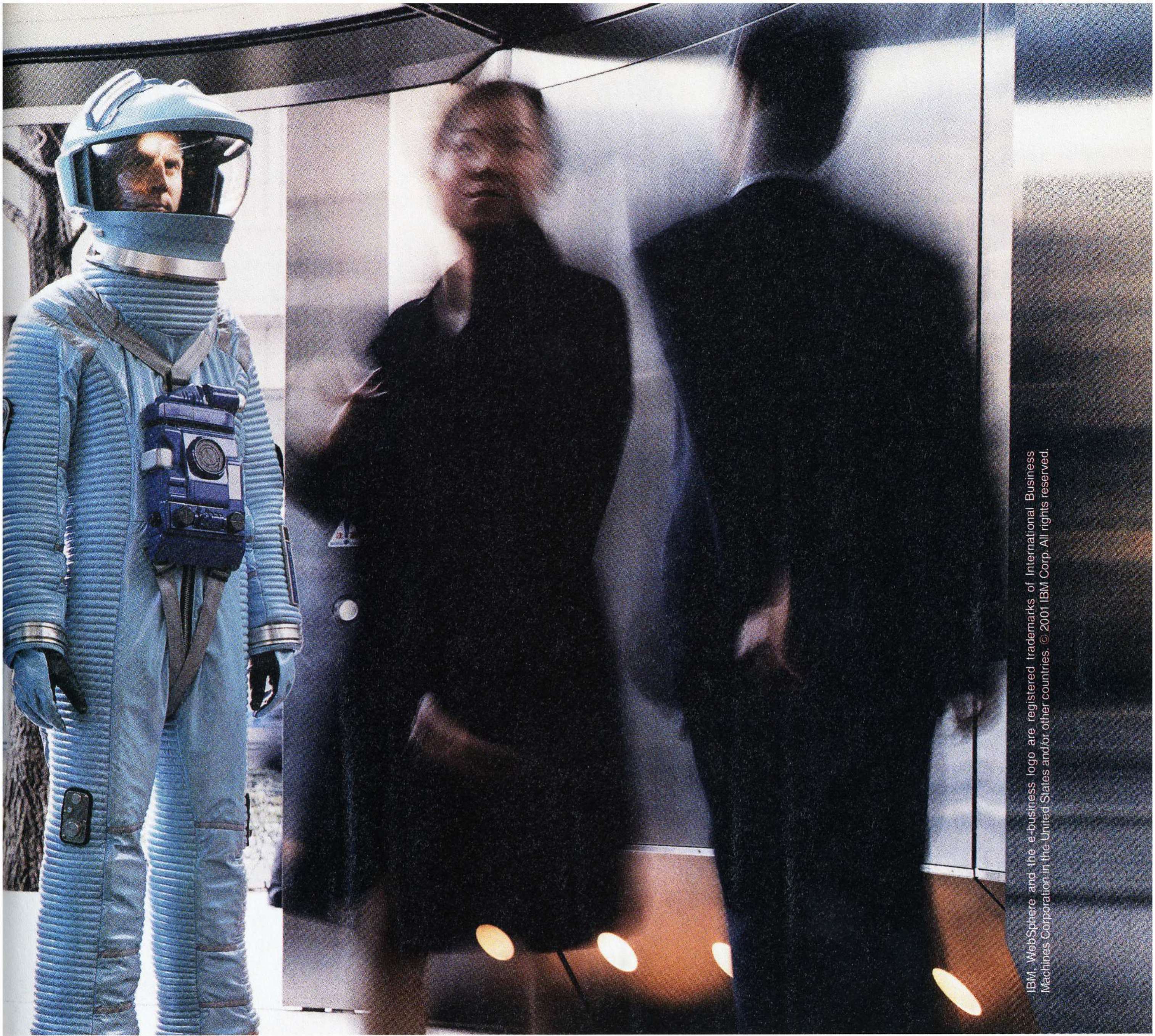

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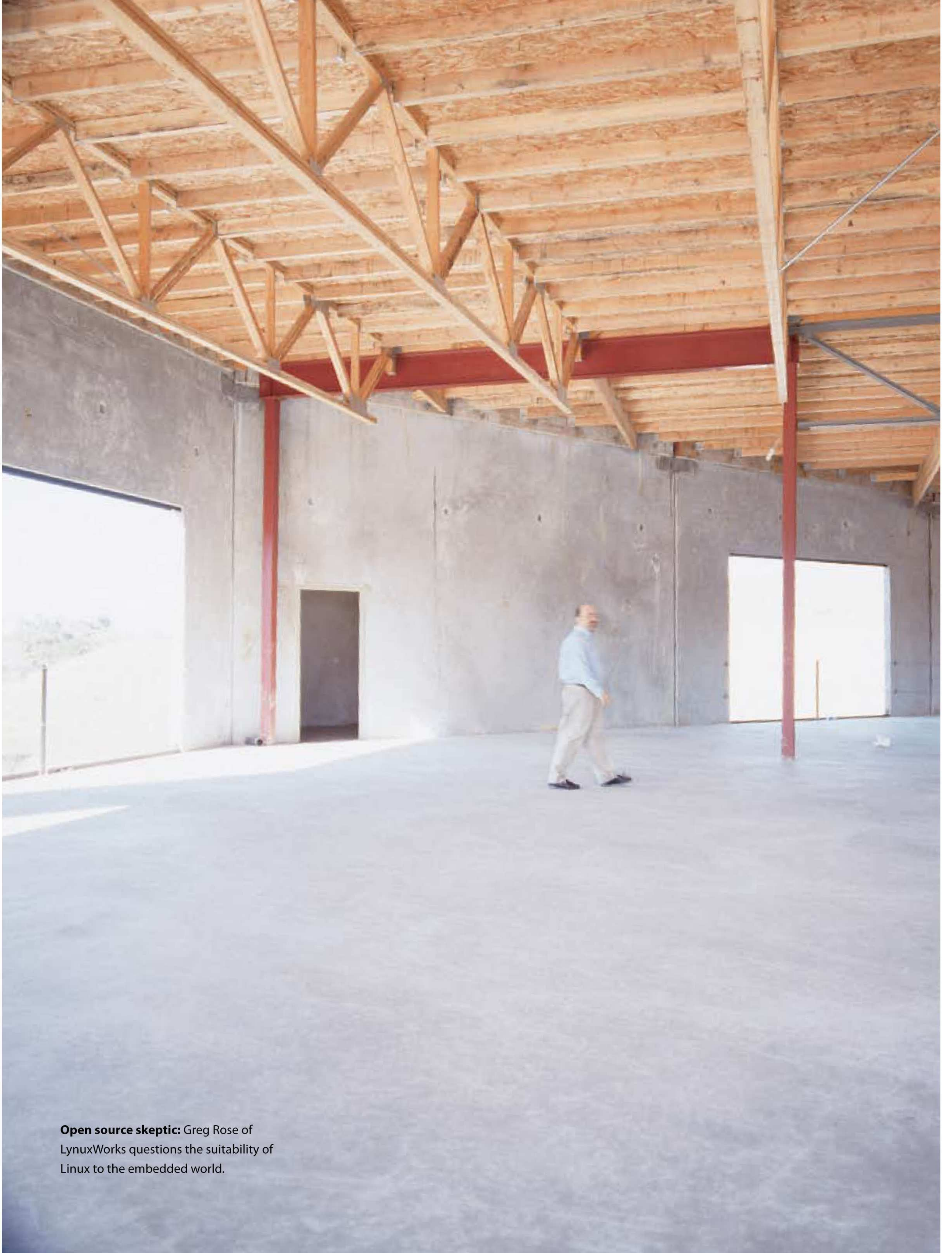


Open source skeptic: Greg Rose of LynuxWorks questions the suitability of Linux to the embedded world.

BATTLE FOR THE UNSEEN COMPUTER

WINDOWS WON THE WAR FOR THE DESKTOP. BUT THERE'S A NEW STRUGGLE OVER OPERATING SYSTEMS EMBEDDED IN EVERYDAY OBJECTS, AND THIS TIME FREE SOFTWARE HAS THE INSIDE TRACK. **BY CLAIRE TRISTRAM**

PHOTOGRAPHS BY ANNE HAMERSKY

Say the word "computer" and most people think of the machine on their desktop—a machine they love, hate, or a little of both. But that notion of computer is going the way of the Univac: less than one-tenth of one percent of all computing devices today have Intel inside, or run Windows. The computers that are having the biggest impact on our lives are the ones embedded in thousands of pieces of equipment that surround us every day. These are the devices that tell our antilock brakes when to unlock. They manage factory automation systems. They tell Tickle Me Elmo when he's being tickled. Soon they will allow our home appliances to diagnose their own malfunctions, and will even call and order their own replacement parts before they fail. These new computers will eventually make a stand-alone desktop system look as anachronistic as the vacuum tube.

But the little smart machines infiltrating our surroundings lack one thing that has made desktop computing so—well, so ordinary. The missing piece is a dominant operating system. Many contenders are already battling for dominance, and it looks as though the proponents of open-source software have a chance to vanquish Microsoft. In some respects, though, the future of

"ubiquitous computing," in which computing power is found in the common objects that pervade our environment, depends less on the particular winner of this battle than on there simply being a winner at all: a common standard that everyone can agree on.

TOO MANY CHOICES

For most casual computer users, the phrase "operating system" conjures up a mental image of the Microsoft Windows screen. But an operating system is not just an arrangement of windows and icons; it is the layer of software that coordinates all actions of the computer. The operating system interprets our inputs and translates them into commands that the hardware understands. In very simple embedded devices, these commands can be etched into the hardware itself (that is the case with the heat sensors in digital thermometers, for instance). But the fastest growing segment of the embedded devices market includes personal digital assistants, Internet-capable cell phones, and other Internet access devices, all of which need operating systems nearly as sophisticated as the one running your desktop computer. Which operating system will dominate these newer devices is still up for grabs.

Microsoft makes two operating systems for embedded devices. One is called Windows CE; the other, Windows NT Embedded. In what must be a humbling experience for the Great Software Monopoly in Redmond, WA, Microsoft's offerings constitute mere slivers of a pie chart along with such geeky names as VxWorks, QNX Neutrino, LynxOS, pSOS and VRTX. In addition, in the last two years more than 40 companies, consortia and academic institutions have begun to distribute versions of Linux for use in embedded devices. As an open-source operating system, Linux is free of licensing costs, available to be downloaded over the Internet by anyone who wants to use it. Linux is sometimes called "free" software, both because of the absence of a licensing fee and because anyone has the right to tinker with the programming code to make it better. In addition to this crazy quilt of choices, nearly half of embedded-systems projects are run on operating systems that developers wrote themselves.

Choice is usually a good thing. Embedded computers, however, provide an exception to the rule. The multiplicity of options is splintering developer talent and making it more difficult to get devices to work together. Many of us have had the experience, for example, of trying to mail a document from a Windows PC to a Macintosh and having the apostrophes disappear; multiply that minor annoyance to imagine how multiple devices in your home of the future might fail to interact. A common operating system could jump-start the innovation process: developers would no longer need to learn a new operating system each time they began a project. Companies could count on hiring people who were already familiar with the operating system.

And all those high-tech gadgets would work together. This consistency is exactly what is needed for the move toward ubiquitous computing—a world where all manner of devices will work together and over the Internet. Your appliances and lighting fixtures of the future might be able to communicate with one another and to load-balance their energy requirements, for example. Or they could order replacement parts over the Internet before a failure occurred. Most of all, they would have a common interface that would save you from needing to relearn how to communicate with them every time you bought something new.

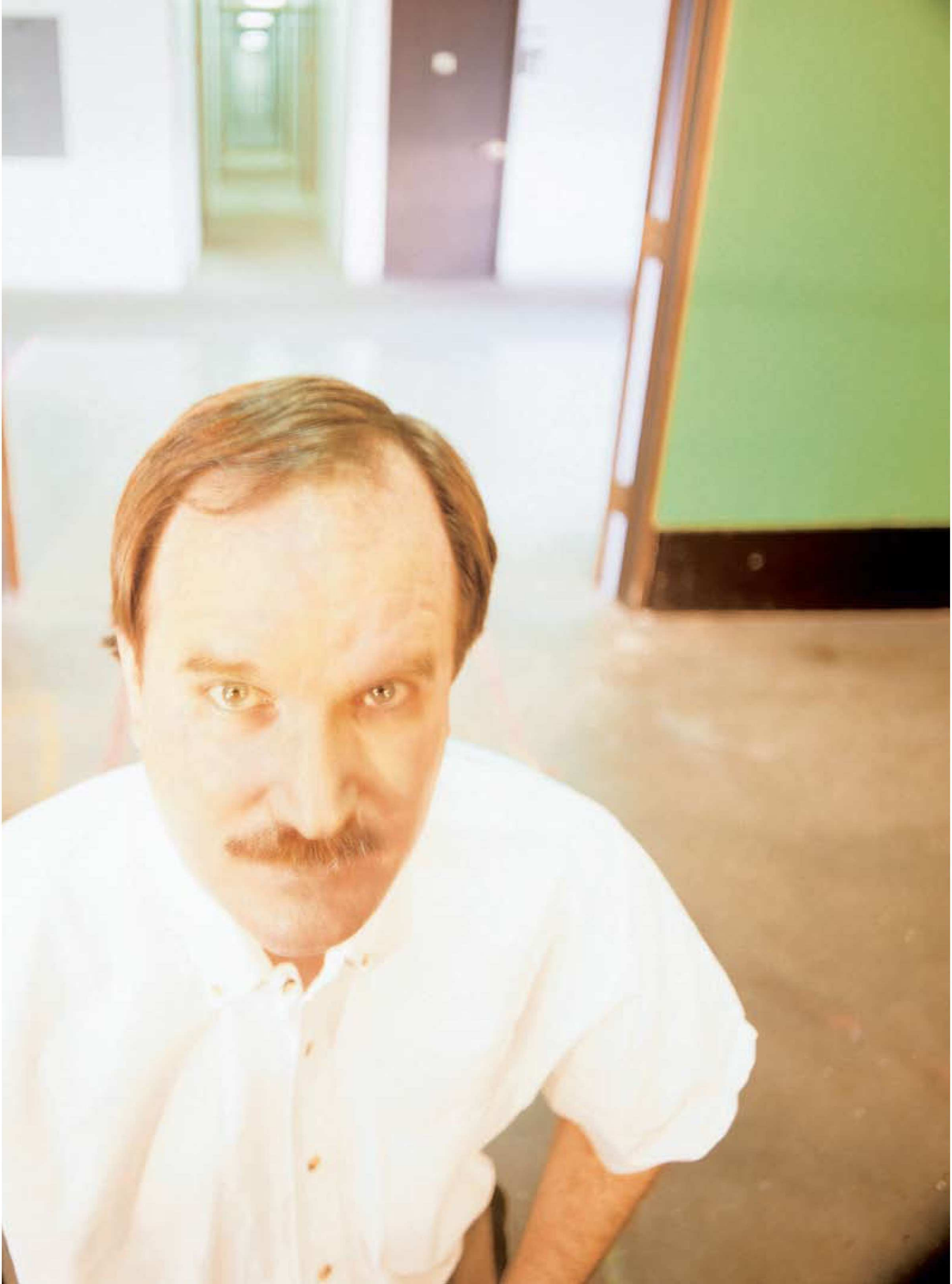
FREE AT LAST!

To Jim Ready, the answer is clear: embedded systems need open-source software. More precisely, they need Linux.

Ready still wears a short-sleeved button-down shirt, the uniform of old-school Silicon Valley before the invasion of Dockers and T-shirts. Back in the early 1980s, he practically invented operating systems for embedded computer systems; his VRTX was one of the first commercial products for embedded systems. He once attended a meeting where an executive at a major chip company referred to Bill Gates as "that pipsqueak."

Even though VRTX still has its fans, Ready is a dedicated open-source zealot. In 1999, he founded MontaVista Software, staking the company's future on the prediction Linux would sweep the embedded computer market much as Microsoft Win-

Betting on Linux: Jim Ready of MontaVista Software is a true believer in the nonproprietary way.



dows did the desktop-PC market. But since Linux is an open-source operating system, this domination could come without all the messy monopolistic overtones that taint Microsoft's position. "Linux is the Switzerland of operating systems," Ready says. "You can move to another vendor if you want, and still use Linux."

"Making the hardware and software work together as efficiently as possible is vital." — see below.

THE SMART LITTLE MACHINES THAT ARE INFILTRATING MORE AND MORE OF OUR SURROUNDINGS LACK A CRUCIAL FEATURE OF THE DESKTOP WORLD: A DOMINANT OPERATING SYSTEM.

Originally created by Linus Torvalds in 1991, Linux code is available to all but obligates developers to make their changes available to others. Linux has benefited from thousands of person-hours of development worldwide and has become the shining example of what's good about the open-source movement. Linux was originally conceived as a desktop operating system, then stretched to fit the computers that work as network servers. Linux's next trick, if Ready is right, will be to shrink into embedded devices like cell phones and PDAs.

Step inside MontaVista's Sunnyvale, CA, facility and you immediately sense you're not in a typical Silicon Valley startup. No one asks you to sign in. You don't need an identification badge or an escort. You can attend engineering meetings at will, without being asked to sign a nondisclosure agreement. Nothing is stamped proprietary. The company takes the open-source movement to heart: its main product is Hard Hat Linux, which MontaVista makes available to customers and competitors alike.

Linux has recently popped up as the operating system powering several high-profile embedded projects, including IBM's prototype of a Dick Tracy-style wristwatch computer, as well as handheld Internet access devices jointly marketed by Gateway and America Online. According to Electronics Market Forecasters, nearly one-third of embedded- systems engineers plan to give Linux a try this year.

The first advantage open-source software gives to developers is access to the so-called kernel—those lines of code at the heart of the operating system. This access is extremely important in the world of embedded computing, where making the hardware and software work together as efficiently as possible is vital.

"Embedded programmers need to know everything, about the hardware, about the operating system, about the application," says Brad Christensen, director of product marketing for Lineo, an embedded-Linux company in Salt Lake City. "With Linux they can see the source. They can reach right into it and change it. It gives them the control they're looking for."

Linux is also attractive simply because it's there for the downloading. Two years ago, San Jose, CA, startup Kerbango wanted to be the first company to produce a stand-alone Internet radio. For months, Kerbango was stuck in contract negotiations with the vendor of a proprietary operating system, stalling the product's development. With nothing better to do, one day an employee decided to download Linux and give it a try.

"He had it up and running on our board ten times faster than it was taking us to get a contract signed," says Carl Hewitt, a founder of Kerbango. In February 2000, the company unveiled the first stand-alone Internet radio. Hewitt estimates that in addition to saving time, the company saved $500,000 in license fees in the first year alone by using Linux. Last year, 3Com bought Kerbango for about $80 million—the brass ring in a summer of soft IPOs. (In March, however, citing the "abruptness and severity of the current technology slowdown," 3Com announced it would be discontinuing Kerbango and other Internet-appliance product lines.)

In addition to sheer accessibility, open-source software offers an unbeatable price. Embedded systems are extremely cost sensitive, and the operating system often needs to cost pennies per unit. That's why, about one-fourth of the time, developers write their own operating systems to avoid licensing fees. An open-source operating system lets them avoid both the fees and the work of writing something completely new.

A final advantage is flexibility: you can change open-source code, as long as you share what you've done. This allows open-source developers to add any little quirk they need to make something work exactly as they want it to. Significantly, this makes it easy to add features that would never hold enough mass appeal to make their way into a general-purpose operating system—such as a single-line command that could align all the solar panels on a space station for maximum energy collection.

If the story stopped there, then Linux and the open-source movement would triumph over all would-be evil empires in the embedded-systems market. That would be the Hollywood outcome with strong sentimental appeal. But despite its advantages, Linux has limitations that even its legions of flag-wavers can't seem to fix. And even open source supporters, in some cases, think the embedded-Linux movement is a shameless waste of energy.

THE ANTI-LINUX

Greg Rose is an odd person to be talking about the limitations of Linux in the embedded market. His company, LynuxWorks, sells it. But the San Jose, CA, outfit is hedging its bets by also selling LynxOS, a proprietary operating system for embedded computing.

While operating systems for embedded devices have remained below the radar screen for most of us, they are technologically elegant. They typically need only kilobytes of memory instead of the megabytes that desktop computer systems like Windows hog. And they can run without anyone telling them what to do—many are in "headless" configurations where there isn't even a user interface. Embedded systems are also built to be fail-safe. After all, a system freeze on a PC is merely an irritation; a glitch in the computer that controls your antilock brakes could be catastrophic.

These operating systems must also be able to perform tasks within a guaranteed window of time. To do this, they interrupt noncritical tasks to make way for critical ones. This feature is known as "real-time" performance. Think automobile bumpers that warn you when you're about to back into something: it doesn't do much good if the alert arrives a second too late. At a refinery that's turning

A middle way: Bill Gatliff is pushing eCos, which combines the advantages of open-source and proprietary software.

crude oil into gasoline, you end up with a big, charred hole in the ground if the right valves don't close when they are supposed to.

It is just such real-time operation that skeptics say eludes Linux. Linux is built to run a given command from start to finish. That's why the embedded systems that run on Linux to date are ones where real time is not critical, such as the Kerbango radio. Disagreement about the best way to make Linux real-time—and whether it's possible to make Linux real-time at all—are splintering the embedded-Linux movement into less-than-friendly factions.

One proposed solution is to run two operating systems in tandem: Linux plus a separate, real-time kernel. This approach is championed by both Lineo and the creators of RTLinux at Finite State Machine Labs in Socorro, NM. One challenge of such a tandem design is how to get the operating systems to communicate. It also forces developers to work in two different operating environments for every project.

MontaVista supports making Linux real-time by creating "preemption points" within Linux itself. At regular intervals of time, the system will interrupt a given task, check for a real-time request, perform whatever operation is being called for, and then go back to the original task. This method is rather derisively known as "soft" real time in the embedded community. "The problem is, between those preemption points, you can't interrupt," says Rose. Preemption, he argues, "works only if when you miss something every once in a while, it's an annoyance instead of a disaster."

Rose maintains that no amount of tinkering will transform Linux, created as a desktop operating system, into one that works well for embedded computing. "If anyone really wants to work with a real-time operating system, Linux isn't going to be the right choice," he says. "To make it work at all you need to add code, and adding code hurts performance." Rose sees Linux as just one more of a long line of operating systems for general-purpose desktop computers—like Unix and Windows—that have tried and failed to make any significant mark in the embedded world. In his opinion they are all too unwieldy and slow. "You can try to make a truck run like a Ferrari, but in the end it's still a truck," he says.

For the last few years, Linux proponents have been pushing in the opposite direction: trying to beef Linux up, not pare it down. This approach has helped Linux gain ground against mature desktop operating systems like Windows NT. But while loading Linux up with features helps it compete against the likes of Windows NT, embedded systems have cramped memories that put a premium on leanness. Slice Linux too far, though, and you end up, not with Linux, but with pieces of Linux. Even its staunchest defenders say Linux can't be reduced to less than half a megabyte; most think two to three megabytes is more realistic. "The moment you start to pull pieces out, you've broken compatibility with the entire world of Linux software," acknowledges Kevin Morgan, vice president of engineering at MontaVista. "You'll never get Linux in a supersmall memory."

RACE TO THE MIDDLE

Despite these limitations, companies selling proprietary operating systems for embedded computers clearly see Linux as a threat. Indeed, some of them are catching the open-source spirit themselves. Last year, for example, Microsoft began to give developers free access to Windows CE for 60 days, so that they could experiment with the operating system in much the same way they can now download and experiment with Linux. Microsoft also slashed licensing costs (though not to zero). Kanata, Ontario-based QNX announced last year that it was going to make its real-time operating system, QNX Neutrino, available for free indefinitely—adding a new twist to the open vs. proprietary battle. QNX plans to allow free use of its operating system for noncommercial projects, while charging royalties for commercial use. Other old-guard companies, including LynuxWorks, will offer Linux alternatives to customers who insist on it, but recommend their own products whenever possible.

So what you have now is something like a race where two runners sprint toward the middle. Proprietary companies are trying to become more open. Linux supporters are trying to make Linux more embedded. But there might be a better solution than either of these: an open operating system that is designed from the ground up for use in the types of embedded computers that are increasingly pervading our world.

Enter eCos, which stands for "embedded configurable operating system." ECos is an open-source, real-time operating system sold by Red Hat of Durham, NC—the leading seller of shrink-wrapped Linux software. "ECos doesn't pretend to be all things to all people," says Bill Gatliff. Gatliff is a software consultant who describes himself as a "free software advocate," even though he is skeptical of embedded Linux. "Everyone talks about Linux having an army of engineers worldwide working on improving the code," he says. "But it's really just a very small number of programmers that are making substantive changes." He says that eCos has "a small set of very good contributors, and that's enough."

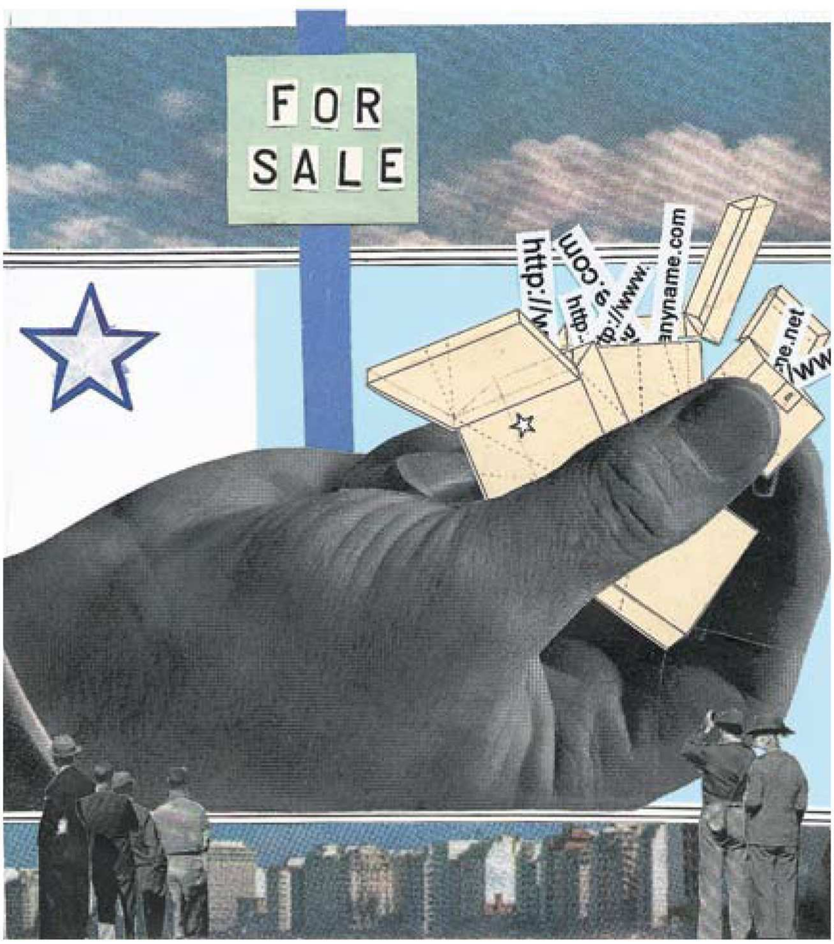
Or perhaps there's a Linus Torvalds-in-waiting, working quietly somewhere on an open-source operating system designed specifically for embedded devices, who is about to post her work on an Internet bulletin board. The Internet is the perfect way to attract a quorum of developers, enough to jump-start the operating system and give it credibility. It sounds unlikely, but then Linux itself seemed implausible before it happened.

Embedded systems will be the next computing paradigm, yet no clear winner has emerged in the current operating-system war. What happens next could tip the scales as to whether free software will prevail over the proprietary kind that has come to dominate the desktop-computing world. The outcome of this conflict will provide important lessons about how computer technologies evolve in the absence of a monopoly. And it will determine how and when we begin to see ubiquitous computing take shape.

Paradoxically, when the perfect operating system ascends into dominance in the embedded-systems market, it will be an anonymous technological wonder that you'll never need to worry about. That's the best kind of technology—something that works so well you forget it's there. Maybe as we leave these desktop-centric years for a world of ubiquitous computing, we'll begin to value computers for the functions they perform, rather than for what's inside. Which is exactly the way it should be. ◊

Dot *What?*

Expect to see some unfamiliar syllables after the dot on the Internet this spring. Besides the .com, .net, .org, .edu, .mil and .gov the world has come to know, seven newcomers are about to enter the fray: .aero, .biz, .coop, .info, .museum, .name and .pro. These additions to the list of so-called top-level domains were approved last November by the Internet Corporation for Assigned Names and Numbers, or ICANN—the closest thing the Internet has to a government. This organization's stated purpose in creating fresh cyber real estate was to open opportunities on the Internet for business and noncommercial use alike. But despite the good intentions behind them, the new dots are likely to remain a footnote in the Internet's evolution.



NICKY ACKLAND-SNOW

Domain names were not part of the original Internet design. They were, rather, an afterthought—created as a techno-fix to a pressing problem by engineers who didn't foresee the long-term implications of their actions. But now, domain names are vital because Web browsers use them as the basis of all navigation. Want to jump to the home page for the White House? Just type the domain name "whitehouse.gov" and off you go. Domain names are the coin of the cyber realm; stories abound of companies trying to buy their domains from so-called cyber squatters, and of large organizations trying to shut down small Web sites because of similar-sounding names.

But the Internet's underlying structure doesn't really use long-winded names to move data about; it uses a compact numbering system. "Whitehouse.gov," for instance, is a human-friendly representation of the address 198.137.240.92. The job of translating the domain names that people type into their browsers into the Internet addresses that the network actually uses falls to an entity called, logically enough, the Domain Name System, or DNS.

The original Internet had no such system. Instead, the addresses for every computer on the Net were kept in a single "hosts" file on a computer at the Stanford Research Institute in northern California. If you had a computer on the Internet, and wanted to maintain an up-to-date version of what else was out there, it was your responsibility to download this file regularly. You can think of the hosts file as the Internet's first white pages.

By 1982, the Internet was growing so rapidly that nobody had a current copy of the hosts file. But there was another problem as well: sometimes more than one computer in the file had the same name. A friend of mine named Martha Rose, for instance, had the mail account "mrose" on the computer "Eddie" at MIT; Martha was forever receiving e-mail for Marshall Rose, who had the same account on a computer named Eddie at the University of Washington. Both computers were in the hosts file under the same name.

The Domain Name System was supposed to solve both of these problems because it is not a single file, but rather a series of files in a database distributed across many computers on the Net. Computers at MIT called name servers hold the Internet directory for MIT; similar servers at the University of Washington hold its directory. The distributed database worked spectacularly well—so well, in fact, that it has not been significantly upgraded in more than 15 years.

The system was also supposed to put an end to naming conflicts of the

sort that vexed my friend Martha. The Internet's engineers created the .edu domain for universities, under which each university would have its own unique sub-domain. Martha's e-mail address became mrose@eddie.mit.edu; Marshall's became mrose@eddie.washington.edu. Likewise, the engineers created the top-level domains .com, .gov, .mil, .net and .org. Because of the U.S.-centric nature of these domains, the system soon expanded to include more than 200 additional top-level domains, one for each country.

Take nearly any word in the dictionary, add ".com," and you'll find that the name is already taken. It will take a lot more than the seven new domains just created to relieve this scarcity.

Trying to be fair, the engineers creating the Internet handed out domains on a first-come, first-serve basis. The University of Washington in Seattle grabbed the domain "washington.edu," forcing Washington University in St. Louis to settle for "wustl.edu." Washington University was good natured about this at the time, but it soon became evident that the Domain Name System was playing by a different set of rules than the offline world.

That distinction stems naturally from the nature of the technology. In the offline world it's possible to have two companies with the same name. But online, every domain name must be unique. Internet domain names are in fact much more like addresses than names. There can be many organizations with the initials MIT, but there can only be one 77 Massachusetts Avenue in Cambridge, MA.

The existence of just one .com domain created an artificial scarcity. Today you can take nearly any word in the dictionary or any common name, add ".com," and you'll find that the domain is already taken. Also taken are practically every combination of two, three, and four characters. Most of these domains aren't being used: they are being hoarded by speculators. Want to use the domain "ieverything.com"? It's yours, for $2,288, from a firm called BuyDomains.com. It is this scarcity that the new domains are meant to curb. And in principle, creating more top-level domains creates more opportunity. "Boston.com" is taken by the *Boston Globe*, but now Boston's art museum can buy "boston.museum." That's a good thing, isn't it?

Not necessarily. For one thing, a mere seven new top-level domains won't make much of a dent in the scarcity problem. Deep-pocketed companies and domain-name speculators will have no trouble buying up Internet addresses in all seven new domains. Then there's the problem of who gets dibs on these names. For instance, should "boston.museum" be reserved for the Museum of Fine Arts, Boston (currently at mfa.org), the Boston Historical Society and Museum (currently at bostonhistory.org), or for some Web-based museum of Boston history that hasn't been created yet?

Many people think that tens of thousands of new domains would end domain-name speculation: it would be prohibitively expensive for the speculators to buy up every word in the English language in every new top-level domain. There are no technical or logistical barriers to creating such a multiplicity of domains, insists Karl Auerbach. An old-time Internet expert, Auerbach was tapped for the names and numbering organization's board of directors last year in what was widely hailed as the Internet's first worldwide election. Auerbach says he set up a demonstration system several years ago that had more than six million top-level domains. The system worked, he says, and showed no loss of speed due to the multiplicity of domains.

Also being criticized is the way that the new domain registrars were chosen. Auerbach advocated giving domains away in a lottery. Others suggested auctioning them off the way the Federal Communications Commission allocates broadcasting frequencies. Instead, organizations that wanted to create top-level domains had to pony up a $50,000 application fee and submit a business plan explaining their planned use of the domain. Some domains were rejected because the names and numbering folks didn't like the plans. "I don't understand why they are interfering with the business models of these organizations," says Michael Froomkin, a professor at the University of Miami School of Law who has written extensively about Internet policy.

I predict that these new top-level domains will remain a novelty, just the way the .to, .tv, .md and .cc domains have been. These belong to small countries (Tonga, Tuvalu and Moldova) and an Australian territory (Cocos Islands) that have decided to open up their name servers to any person or company wishing to make the purchase. But despite massive publicity campaigns (often conducted through e-mail spam), these domains have failed to catch on.

The fact is, people in the United States are comfortable with the .com domain, just the way people in England are comfortable with .co.uk. Instead of searching for new top-level domains, businesses are living with the shortage of names, and making do. Meanwhile, when a new company is named, or when an existing company is renamed—something that seems to be happening a lot—the availability of a dot-com address is a central part of the process. We are changing the way that we do business, and the way we think, in order to deal with the limitations of the computer systems that we have created.

Companies will probably continue to struggle with the artificial scarcity of the .com. They will keep coming up with unique domain names, by coining new words and obscure combinations of letters and numbers. It will be easier to do that than to teach consumers to type ".biz." ◊

Holographic Memory

Laser beams store data in three dimensions

STACKABLE STORAGE. IT'S THE ULTIMATE SPACE SAVER, MAKING ORDER out of chaotic cabinets, closets, attics and garages. But until recently it had not made its way into the realm of computers, where megabytes of data are scattered on the face of a disk like millions of shoes across a bedroom floor.

Now a few big-name media makers, including Lucent Technologies and IBM, are making important strides in developing optical holography, which stacks information throughout the thickness of a storage medium, instead of just writing it to the surface.

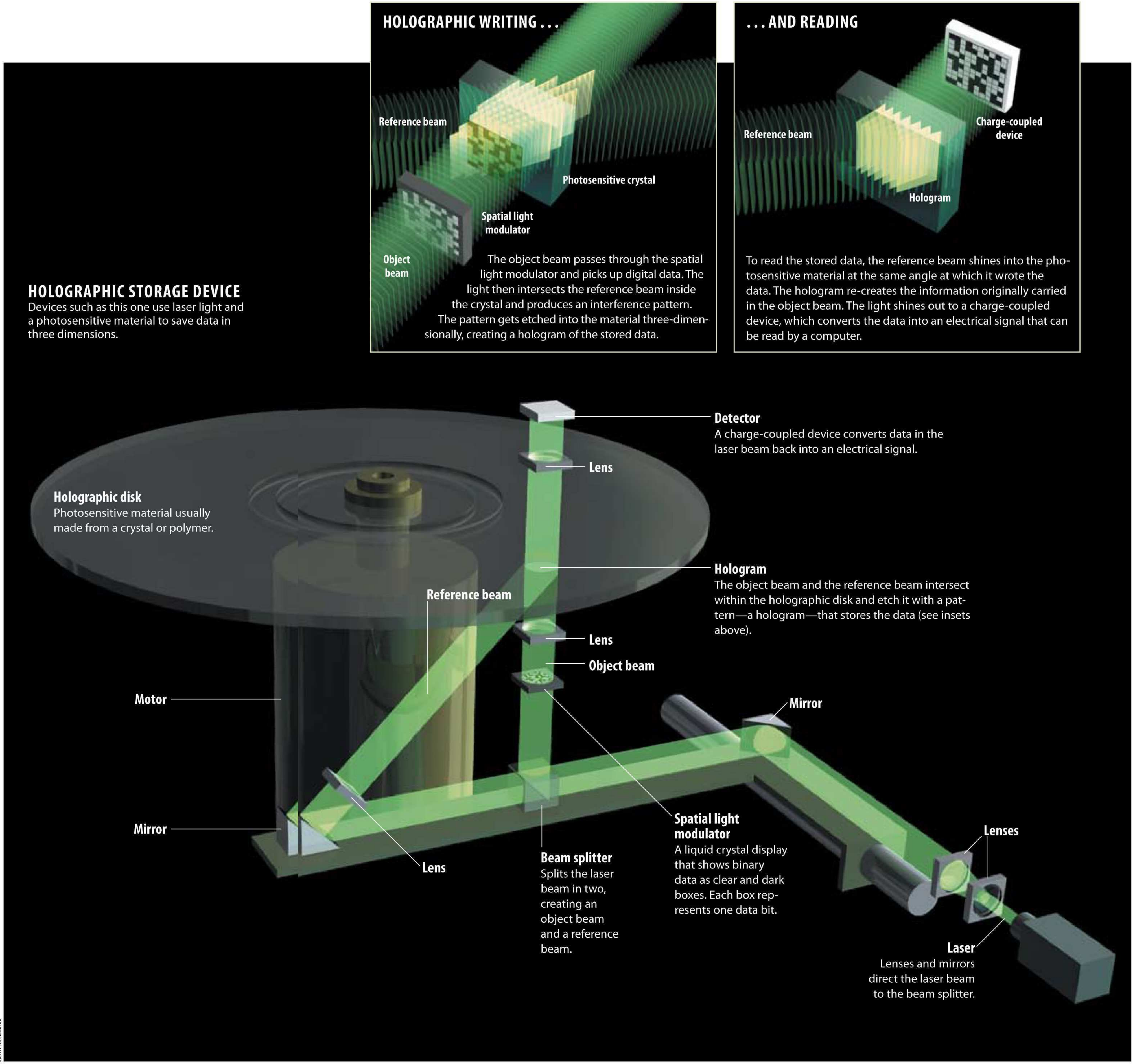
COURTESY OF IBM ALMADEN RESEARCH CENTER

Holographic storage relies mainly on laser light and a photosensitive material—usually a crystal or a polymer—to save data. It works by splitting a laser beam in two. One beam contains the data and is referred to as the "object beam"; the other holds the location of the data and is known as the "reference beam." The two beams intersect to create an intricate pattern of light and dark bands. A replica of this so-called interference pattern gets engraved three-dimensionally into the photosensitive material and becomes the hologram. To retrieve the stored data, the reference beam is shone into the hologram, which refracts the light to replicate the data beam.

The holographic technique packs data so tightly that one 12-centimeter disk could eventually hold a terabyte of data—about as much information as 200 DVDs. What's more, holographic storage opens the possibility of reading and writing data a million bits at a time, instead of one by one as with magnetic storage. That means you could duplicate an entire DVD movie in mere seconds.

The idea of storing tons of data three-dimensionally was first proposed by Polaroid scientist Pieter J. van Heerden in the 1960s. But developing the technology was difficult, because the required optical equipment was large and expensive. A typical laser back then, for example, was two meters long. Today, lasers are measured in mere centimeters and are much cheaper.

Holographic storage equipment is not yet produced commercially, but the technology has the potential to spawn new devices and systems. It could supplant DVDs, allow people to save information on 3-D disks, and enable researchers to sift through enormous databases in the blink of an eye. The future may not be that far off, either. Recently, Lucent launched a new venture, InPhase Technologies, to develop holographic storage, and plans to have a product on the market in a couple of years. ◊



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TV Tomorrow

When I tell people that I teach television, they sometimes boast, "I don't even own a TV set!" All I can say is that we inhabit different realities.

I read Phillip Swann's *TV dot Com: The Future of Interactive Television* with the same sense of looking across a vast cultural divide. Swann, the former publisher of *TV Online* magazine, thinks interactive television should and will be designed for channel zappers: "Few viewers today can sit through an entire program without picking up the remote and checking out another channel."

In Swann's future, variety and magazine shows will almost entirely displace dramas, and the few remaining series will be shrunk to 30 minutes or less, reflecting dwindling attention spans. VCRs will be "shelved forever" once the hard drives for personal videorecorders "expand to permit consumers to store dozens of hours of programming." Swann devotes an entire chapter to the silly idea that viewers will want to disrupt the flow of *Ally McBeal* in order to buy, right then and there, whatever Ally happens to be wearing.

I wish I could dismiss Swann as an eccentric, but similarly bad ideas are circulating in Hollywood too. The future of interactive television is being designed by and for people who don't care for television. One researcher brags he can compress any show into half its original length. In his perfect world, television might consist of nothing but coming attractions. According to Swann, "People will start watching TV shows the way they read books: a little at a time." Such plans reflect an impoverished understanding of television viewing and a lack of interest in the medium's aesthetics.

Historians of the book make distinctions between intensive and extensive readers. In the older manuscript culture, a reader had access to only a few works but read them closely and over years. With the rise of printing, this intensive reading was theoretically displaced by extensive reading: readers read more books and spent less time on each. But intensive reading never totally vanished. Ask around and you'll probably find someone who rereads *Gone with the Wind* or *The Lord of the Rings* every year.

Television enthusiasts have the same desire for intensive engagement. The new media environment encourages some restless viewers to channel-surf. But it also supports prolonged involvement with series. The VCR produced a nation of video collectors. When the full run of *The Simpsons* spans hundreds of hours, why be satisfied with a technology that can only hold a few dozen episodes? We are more likely to use TiVo—a personal interactive television service that uses a digital recorder—to watch television and use videotape (or some equivalent storage medium) to archive it.

The availability of such digital recorder-based services may partially "liberate" us from the network schedule, yet this does not spell the end of "appointment" television any more than videotape rentals decrease the length of movie lines on opening night. We watch television in part so we can talk about it, and we want to see it when everyone else does so we don't have the good parts spoiled by other people's big mouths.

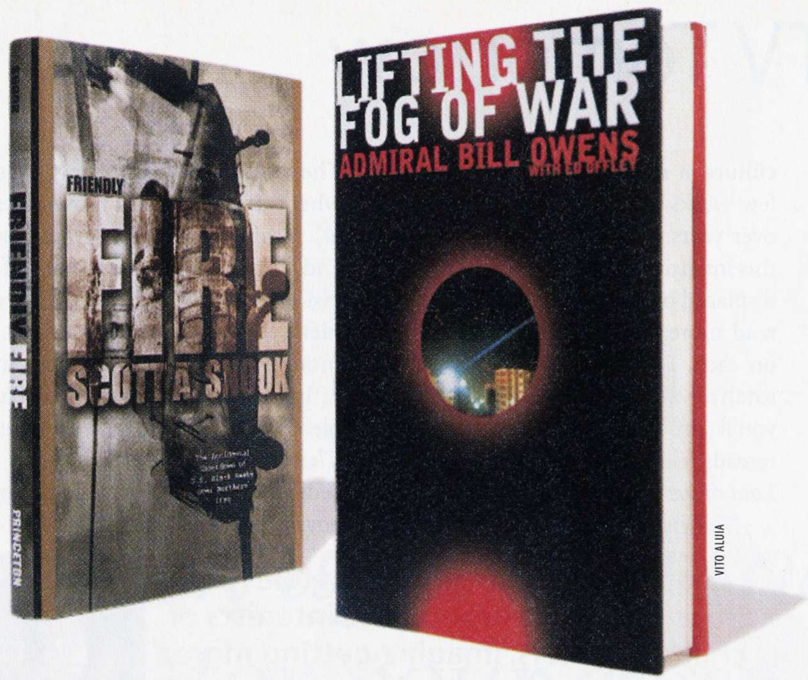
TiVo wisely targets both extensive and intensive viewers. It allows us to pause a live TV broadcast, do something else, and return to watching where we left off. But we can also book "season passes" to favorite series. The technology tracks down episodes wherever the network moves them.

While Swann imagines shorter and shorter series, the history of television drama suggests growing complexity, more elaborate story arcs, more back story. Among the current ratings champs are serialized ensemble dramas like *ER*, *The Practice*, and *The West Wing*—series Swann concedes would not survive in the media environment he describes.

Don't assume the future of television has to revolve around the interests of channel surfers. Imagine getting more, not less, from the shows we watch.

But I believe interactive television could support even more serialization. Imagine a world where reruns could be downloaded, enabling latecomers to catch up on cult serials. Imagine being able to click on the screen and replay scenes from earlier episodes that reveal back story—say, all the scenes from *The X-Files* dealing with the disappearance of Mulder's sister. Imagine annotations by both fans and producers. Imagine a new economics of television that supports many more shows, where a series with a small but committed group of intensive viewers—which couldn't cover the overhead costs of broadcast TV—could thrive via a download medium. In other words, imagine getting more, not less, from the shows we watch.

Undoubtedly, there will be new media forms that reflect the interests of channel surfers. But don't assume this represents the only direction for tomorrow's television. Swann envisions a future marked by diversity of media choices and yet a sameness of viewing styles, an audience eager to buy Ally McBeal's skirt but not to watch an entire hour-long episode. As I said, we inhabit different realities. ◊



VITO ALUIA

BOOK REVIEWS | MICHAEL SCHRAGE

War's Coming Digital Fog

Battlefield "transparency" isn't all it's cracked up to be

FOR THOSE WHO HAVE ENdured combat, Carl von Clausewitz's classic military metaphor about "the fog and friction of war" needs no explanation; it's a truism. For those of us who have never served, the line is only understood rationally. No doubt the tone and tenor of this review would have been different if it had been written in the guts of an Apache helicopter or Abrams tank on a combat mission. Then again…

Lifting the Fog of War is both title and theme of Admiral Bill Owens's smoothly written and crisply argued book about what America's high-tech military infrastructure should be. The admiral—vice chairman of the Joint Chiefs of Staff during the first Clinton administration and commander of the U.S. Sixth Fleet during the Gulf War—is a champion of both technological and organizational innovation. In fact, he wants them integrated. He wants new command and control infrastructures to redefine communication and coordination between and within the services. He proposes joint forces training, exercises and initiatives to annihilate anachronistic army, navy, marine and air force doctrines. His harsh—but astute—interpretations of the technical and interservice conflicts surfaced by the Desert Storm and Kosovo conflicts merit particular attention. Owens doesn't flinch from critiquing his civilian counterparts either.

Unsurprisingly, Owens grasps the nettle of the cultural and institutional politics that both thwart and enable military innovation. The pleasant surprise is that his comments are candid without being cutting. And they're targeted at an *Economist*-type audience—not just the Brookings or Georgetown defense policy crowd. Even the endnotes are informative and entertaining.

> **BOOK:** *Lifting the Fog of War*
> **AUTHOR:** Admiral Bill Owens, with Ed Offley
> **PUBLISHER:** Farrar, Straus and Giroux, $25
>
> **BOOK:** *Friendly Fire*
> **AUTHOR:** Scott A. Snook
> **PUBLISHER:** Princeton University Press, $35

While *Lifting the Fog of War* isn't propaganda, Owens's ideological bias and technical sensibility make it a policy polemic. In particular, he promotes the "revolution in military affairs" doctrine, a profound effort to redefine America's war-fighting architecture that has provoked superheated debate inside America's military-industrial complex and the national-security community.

The revolution in military affairs premise? Technology should make the battlefield "transparent"; mobility should be as treasured as mass; weapons should be made smarter and the people who wield them smarter still. The chain of command should be preserved, but warriors must be rigorously trained to improvise. Technology and tactics should coevolve and not be held hostage to annual budget battles and internecine interservice conflagrations. Procurement cycles for cutting-edge technology must shrivel. Innovation—not the preservation of military tradition—should drive doctrinal debates.

While these aspirations are bold, their implementation has been tepid. "Even as we built a consensus on what was needed to jump-start American military power into the twenty-first century," Owens writes, "we knew that the White House and many congressional leaders were bent on drastically reducing defense spending whatever the cost to our national security." Long-term research and development projects fell behind. Humanitarian missions and peacekeeping assignments ran forces ragged. The U.S. revolution in military affairs appeared bankrupt before it had gotten started.

Yet the Bush administration, with supporters of revolution in military affairs-type initiatives playing key roles in the Pentagon, may reverse that trend. Certainly, Owens's vision of bandwidth-rich battlefields where commanders can real-time track their own personnel—and the enemy's—is compelling. The belief that tomorrow's technology can, indeed, lift "the fog of war" is powerful.

But the battlefields of tomorrow's hell may be digitized with good intentions. I have never been in battle nor commanded men with lives at risk. On the other hand, I have had the opportunity to see exactly what happens when technology makes a workplace or a marketplace more "transparent."

Yes, there are benefits; but oftentimes, transparency creates more conflict than it resolves. Reread Owens's own assessments of Desert Storm and Kosovo and it becomes clear that greater transparency and more just-in-time information would have been tremendously useful at key points during those wars. But it's equally clear that many of the most significant conflicts within the military and civilian command structures revolved around differing interpretations of excellent data.

In essence, the disagreements were driven as much by fundamental differences in values and perceptions as by data gaps, ambiguity or ignorance. This is only logical. As this is written, there is another global battle being waged that costs the combatants tens of billions of dollars a year. The warriors are better paid and better trained than Top Gun pilots or Navy SEALS. They, too, fight to win. They, too, fight to preserve tradition even as they struggle to adopt bold innovations. Most importantly, these warriors totally believe in "information warfare," the "need for speed" and lifting the "fog of war."

Forgive the analogy, but I'm talking about the global financial system's networks of ruthless traders of currencies, equities and debt. These combatants have access to the same information but—guess what?—for every buyer there is a seller. In other words, brilliant people have access to near-perfect data in their near-transparent battlefields (certainly more transparent than any military battlefield), and yet they come to completely opposite conclusions about what to do next.

Similarly, even if admirals and generals had perfect real-time battlefield perspectives, the fog of war would persist. Sure, leaders could see things more clearly—but this digitized fog might be even more dangerous. Why? Because

transparency renders battlefield issues inordinately more complex.

True story: During the Gulf War, for the first time in American warfare, practically everyone who needed radio access had it. When one of the first battles began, communications were immediately clogged because everyone tried to communicate simultaneously. It took hours to establish a wireless hierarchy protocol. Question: Should every soldier have radio access? Should a soldier be able to skip the chain of command? What happens when the army, navy, air force and marines interpret precisely the same data in fundamentally different ways? This problem persists whether communications are excellent or not.

It is the failure to appreciate the profound nature of such questions—which fire at the heart of the proposed revolution in military affairs—that forms the flaw in Owens's book. Sadly, though, many of the answers were provided on April 14, 1994, when two U.S. Air Force F-15 fighters shot down two U.S. Army Black Hawk helicopters over northern Iraq, killing all 26 peacekeepers on board. This accident and its subsequent exhaustive investigation are chillingly reconstructed and analyzed by Lieutenant Colonel Scott A. Snook in *Friendly Fire,* which should be required companion reading for Owens's book. And Snook, an army officer who was himself a victim of friendly fire in Grenada, comes to a telling conclusion.

Many significant command conflicts revolve around differing interpretations of excellent data.

"Sifting through the mountain of data, no smoking gun emerged," he writes. "There weren't any bad guys; hence, no one to blame. There weren't any catastrophic failures of material or equipment; hence, nothing to fix....The more I looked for traditional culprits, the more I realized that this accident occurred not because something extraordinary had happened, but rather just the opposite."

In fact, Snook cleanly describes a painful litany of technical, individual and organizational mini-breakdowns. The Identification, Friend or Foe transponder on the Black Hawks apparently didn't work. An experienced F-15 pilot misidentified the helicopter. The AWACS crew—which enjoyed precisely the kind of high-tech, high-bandwidth transparent battlefield and air space Owens envisions—seldom trained as a team, and its leaders often skipped simulation runs. The army's helicopter missions were seldom integrated into the air force's mission "packages." Etc., etc., etc.

So was this accidental shoot down a "transparency" issue? A command and control issue? A training issue? An interservice rivalry issue? The answer, of course, is "all of the above." But what does that tell us? One interpretation is that "transparency" is badly overrated as a virtue if military cultures don't address the cultural and organizational fundamentals. Another is that there is a dangerous belief that if we give more smart people more smart information and more smart weaponry, a consensus will emerge on what to do with it all. In fact, the opposite will likely occur, and this will breed even more intense disagreements over what to do next. Why? Because it will bring even more to the fore the genuine and legitimate differences in philosophies, doctrines and values that divide the armed forces branches.

I would pay good money to read a review of Admiral Owens's book by Lieutenant Colonel Snook and a review of Snook's book by the admiral. I think each would be sobered and tempered by the other's insights. One can only hope that the nation's military and new civilian leadership actively encourage that kind of rigorous reexamination of these fundamental issues for tomorrow's conflicts. The fog of war is an excellent reason to promote as clear and transparent a debate on these questions as possible. TR

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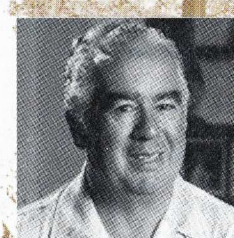

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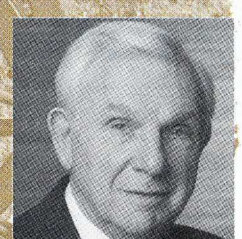

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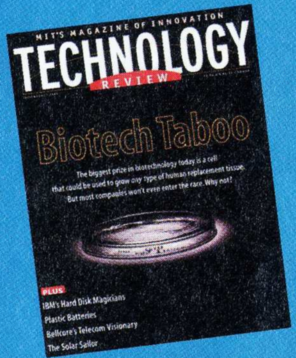

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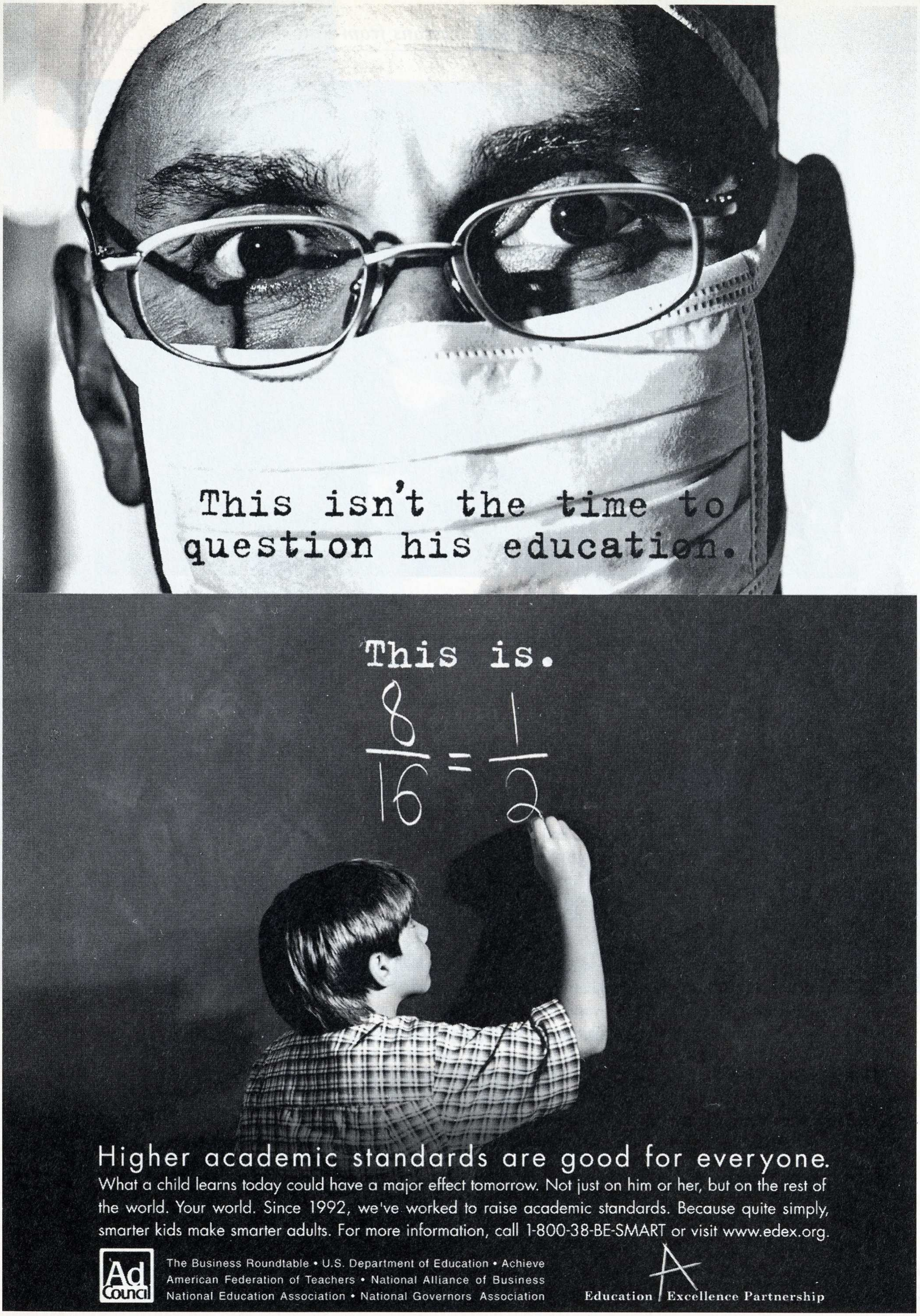

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A Very Long Distance

A regulatory call put cell phones on hold

When cell phones first became commercially available in the United States in 1983, an explosion of sales soon followed. Today, cell phones are a $40 billion industry; one out of three people in the United States carries one in a pocket or a bag. But were it not for regulatory red tape, cell phones might have been available to high-tech swingers in the 1960s.

As far back as 1947, AT&T had developed the basic cellular concept: a network of small geographical areas with a low-powered transmitter in each to serve mobile phones. Looking to the future, the company asked the Federal Communications Commission to allocate more frequencies for the CB-radio-like car phone; once car phones with trunk-sized receivers became a mass phenomenon, AT&T reasoned, there would be a financial incentive to pursue more portable technology. (The transistor would be introduced by AT&T's Bell Labs that same year.)

The FCC was unimpressed, however, and in 1949 allocated only a few more channels for mobile-phone use. Car phones, the FCC declared, were "more in the nature of convenience or luxury," and less in the "public interest." The result: each service area could handle only 23 mobile calls at any given time. Companies elected not to waste their time developing mobile phones for such a limited market.

It took almost two decades for regulators to reconsider. In 1968, to alleviate congested mobile-phone frequencies, the FCC made a proposal to telecommunications companies: if they could demonstrate a truly efficient, high-capacity mobile-phone service, the FCC would allocate the large number of frequencies necessary to make the service commercially viable. Research accelerated, and Motorola and Bell Labs spent millions in a race to incorporate cellular technology into usable devices. In 1973, Martin Cooper of Motorola let his rivals at Bell Labs know who won—by calling them up on a prototype handheld cell phone.

It took two more years before the FCC green-lighted the first trial cellular system, and it wasn't until late 1982 that fully commercial cellular service was allowed in the United States. (Spectrum Cellular's early portable phone is pictured above.) By that time, commercial service had already been established in several European countries, Japan, and even tiny Bahrain. Since then, the cell-phone industry has become one of the fastest growing in history. But if the FCC hadn't slowed the process, we might have been using cell phones 20 years earlier. ◊

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